

Infant Hyperacuity for Radial Deformation

Eileen E. Birch,^{1,2} William H. Swanson,^{1,3} and Yi-Zhong Wang^{1,2}

PURPOSE. Poor response rates and/or the confounding of motion and offset responses make it difficult to interpret results of previous studies of infant hyperacuity. The aim of the present study was to design a protocol that overcomes these limitations and to investigate the normal maturation of hyperacuity.

METHODS. Hyperacuity of 31 healthy term infants aged 4 to 12 months was measured using radial deformation of static circular D4 patterns with a two-alternative, forced-choice, preferential-looking (FPL) protocol and maximum likelihood threshold estimation. FPL grating resolution acuity was assessed on the same visit.

RESULTS. Both hyperacuity and resolution acuity were 1.1 to 1.2 logMAR (12–16 minutes arc) at 4 months of age. Hyperacuity improved rapidly to approximately 0.3 logMAR (2.0 minutes arc) by 9 to 12 months of age. This 0.9 log unit improvement in the hyperacuity still leaves the 12-month-old infant at a level 0.4 log unit poorer than adults' thresholds. Resolution acuity improved more gradually to approximately 0.7 logMAR (5 minutes arc) by 9 to 12 months of age. This 0.4 log unit improvement leaves the 12-month-old infant at a level 0.6 log unit poorer than adults' resolution acuity.

CONCLUSIONS. Hyperacuity measured via radial deformation thresholds matures very rapidly between 4 and 6 months of age and continues to mature more slowly throughout infancy and into early childhood. The radial deformation protocol may provide a sensitive index for detecting and monitoring abnormalities in spatial vision in cases of infantile esotropia. (*Invest Ophthalmol Vis Sci.* 2000;41:3410–3414)

Strabismic amblyopia often begins during the first year of life. However, there are currently no good quantitative methods for early detection of strabismic amblyopia or for monitoring the effectiveness of amblyopia treatment during infancy. Infant grating acuity test protocols are insensitive to strabismic amblyopia; strabismic infants with strong fixation preference consistent with amblyopia often show little or no grating acuity deficit during the first year of life.^{1–3} For example, in a recent analysis of various interocular grating acuity difference criteria for detection of amblyopia, accurate detection of amblyopia ranged from a low of 0% to a high of 60% for forced-choice preferential looking and swept visual evoked potential data sets.⁴ During occlusion therapy for strabismic amblyopia, grating acuity may even show reversals, that is, poorer preferred eye grating acuity and improved nonpreferred eye grating acuity, which are inconsistent with fixation preference and recognition acuity measures of amblyopia.^{5,6}

Adults with strabismic amblyopia show more profound impairment of vernier acuity than grating acuity with a consequent large reduction in the resolution/vernier ratio.^{7,8} Greater impairment of vernier acuity than grating acuity has been

interpreted as evidence for spatial undersampling and/or irregular sampling in strabismic amblyopia.^{9,10} The relatively greater impairment in vernier than grating acuity provides a basis for the hypothesis that vernier acuity test protocols may have higher sensitivity than resolution acuity for detecting and monitoring spatial vision deficits in infantile strabismic amblyopia.

Several infant vernier acuity tests have been reported in the literature.^{11–20} However, these electrophysiological and psychophysical studies of vernier acuity in normal infants have been limited by poor response rates and/or confounding of motion and offset responses. In those vernier acuity protocols that used static offsets,^{11,13,14,19,20} many infants were unable to complete the test protocol and many of those who were able to complete testing provided low upper asymptote or a small number of trials (yielding poorly defined psychometric functions). In an effort to better capture the infant's visual attention, some paradigms added temporal jittering to the offsets.^{12,15–19} The addition of temporal jitter did have the intended effect of yielding higher test success rates and better upper asymptotes for psychometric functions. However, there remained some infants were unable to complete the test protocol and the addition of jitter to the stimulus had the unwanted effect of making it difficult to unambiguously interpret responses as mediated by detection of spatial offsets rather than detection of motion cues.

Recently, a paradigm for detection of static radial deformation of D4 (fourth derivative of a Gaussian) circular contours has been described.²¹ Adults perform this task as a hyperacuity; for example, for a 5 c/deg peak spatial frequency D4 pattern of 0.5° radius, the radial deformation threshold is less than 10 seconds arc.²¹ Over large ranges of D4 peak frequen-

From the ¹Retina Foundation SW, Dallas, Texas; ²Department of Ophthalmology, University of Texas Southwestern Medical Center, Dallas; and ³Department of Clinical Sciences, State University of New York College of Optometry, New York, New York.

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Corresponding author: Eileen E. Birch, Retina Foundation of the Southwest, 9900 N. Central Expressway, Suite 400, Dallas, TX 75231. ebirch@retinafoundation.org

cies, radii, and radial deformation frequencies, radial deformation threshold is a constant Weber fraction of the D4 radius ($\sim 0.3\%$).²¹ Evidence suggests that discrimination of static radial deformation of D4 circular contours, unlike more traditional vernier acuity tasks, is performed as a global shape detection task.^{21,22} Adults with strabismic amblyopia show radial deformation threshold deficits in this protocol consistent with the severe losses shown in more traditional hyperacuity tasks.²²

The aim of the present study was to develop a protocol for evaluating infant vernier acuity that has high response rates and is free from the confounding effects of motion so that we can define the normal maturation of hyperacuity during the first year of life. Our hope was that the static radially deformed D4 patterns would be sufficiently attractive to infants that the infants would prefer to look at them rather than at the plain circular contours. We found a strong preference for looking at the radially deformed D4 patterns. The achievement of this aim is the first step toward a paradigm for the study of the earliest stages of infantile strabismic amblyopia.

METHODS

Subjects

Thirty-one healthy term infants aged 4, 6, 9, or 12 months participated. In addition, six healthy adults aged 24 to 47 years participated to provide comparison groups. Informed consent was obtained from one or both parents before the child's participation. This research protocol observed the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board of the University of Texas Southwestern Medical Center.

Stimulus

A sample circular D4 stimulus pair is shown in Figure 1. The patterns are defined by four parameters: D4 peak spatial frequency, radius, radial frequency, and modulation amplitude. Peak spatial frequency, which defines the width of the circular contour, was set to 1 c/deg to be well within the grating acuity limit for even the youngest infants tested in the present study. Radius, which defines the size of the circle, was set to 3° , based on pilot data from infants that suggested that the stimuli of this size were attractive to the infants yet could still be presented with sufficient spatial separation on a video monitor to allow for reliable forced-choice preferential looking responses. Radial frequency, which defines the number of deformations present around the circumference of the pattern, was set to 8 based on pilot data from infants that suggested that this frequency elicited robust preferential looking responses. The peak spatial frequency, radius, and radial deformation frequency used in the present study are within the range over which the adult Weber fraction is constant and 0.3% of D4 radius.²¹ Mean luminance was 1.52 log cd/m².

Protocol

On each trial the infant was presented a static circular D4 pattern deformed by radial sinusoidal modulation paired with an undeformed static D4 pattern. When the deformation was large, infants consistently preferred to look at the deformed circle. Radial deformation thresholds were assessed using a 2-down-1-up staircase forced-choice preferential looking protocol,²³ varying modulation amplitude. An observer, who was

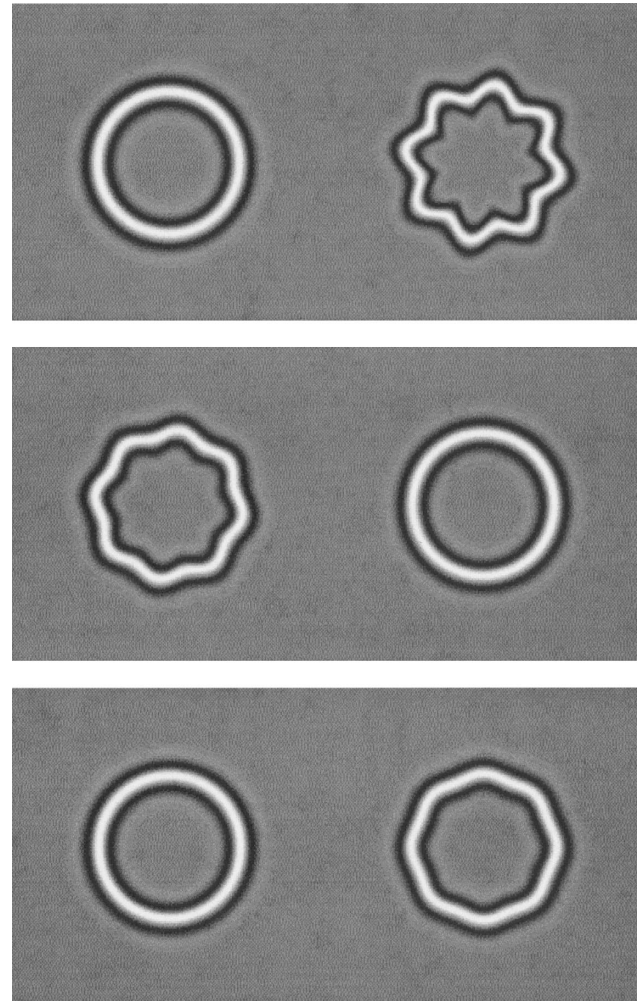


FIGURE 1. Sample circular D4 stimulus pairs. The patterns are defined by four parameters: D4 peak spatial frequency (width of the circular contour; 1 c/deg), radius (size of the circle; 3°), radial frequency (the number of deformations present around the circumference of the pattern; 8), and modulation amplitude. The three examples shown illustrate stimulus pairings of 0% modulation with 10% (*top*), 5% (*middle*), and 2.5% (*bottom*) modulation.

unaware of the left-right location of the two patterns, watched the infant and made a forced-choice decision on each trial regarding which pattern was preferred by the infant. When the observer indicated the decision by joystick, the trial ended. When the deformation was large, infants consistently preferred to look at the deformed circle. On average, a complete staircase included 33 trials (SD = 7 trials). Thresholds were determined by performing maximum likelihood estimation on the staircase data sets using a three-parameter model of the psychometric function²⁴:

$$R(x) = \gamma P(x) + 0.5[1 - P(x)]$$

in which γ is the upper asymptote of $R(x)$ and

$$P(x) = 1 - 2^{-(x/\alpha)^\beta}$$

where α is threshold and β controls slope.

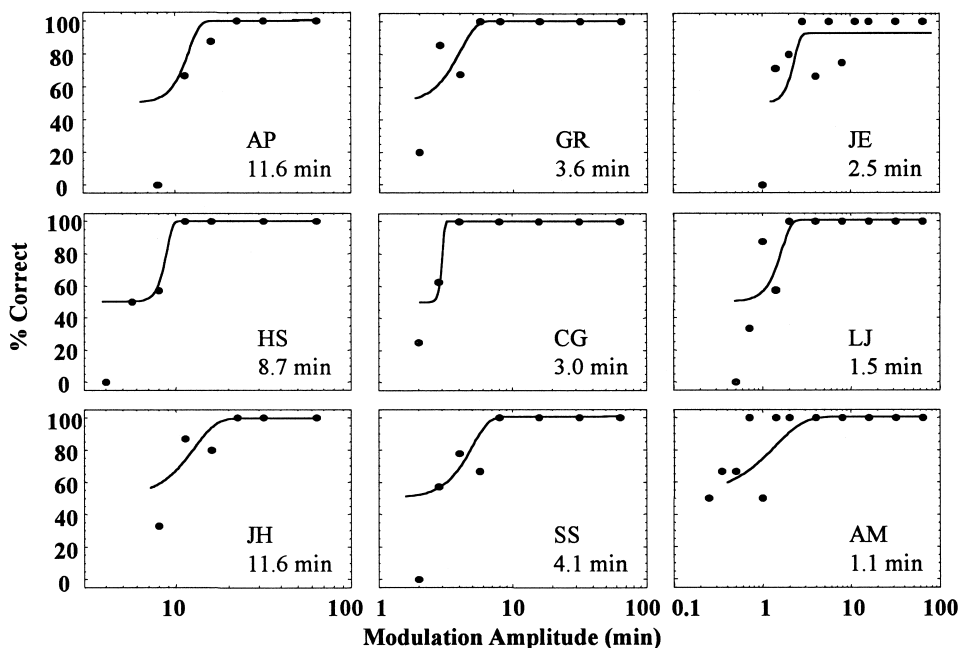


FIGURE 2. Sample psychometric functions obtained from nine of the infants tested. *Left:* 4-month-old infants; *center:* 6-month-olds infants; *right:* 9-month-old infants. Note that, because data were gathered with a two-alternative, forced-choice staircase, many of the data points at the largest and smallest values of radial deformation are based on only a few trials; the staircase protocol focuses data collection at values of radial deformation at and slightly above threshold.

Grating Acuity

Grating acuity was assessed during the same visit using Teller acuity cards and a 2-down-1-up staircase forced-choice preferential-looking protocol.²³ Mean luminance of the acuity cards was 1.60 log cd/m². Thresholds were determined by performing maximum likelihood estimation on the staircase data sets using a three-parameter model of the psychometric function.²⁴

RESULTS

Psychometric Functions

The success rate for the test protocol was high, with only 2 (6.5%) of 31 infants (one 4-month-old and one 12-month-old) failing to complete both the radial deformation and grating acuity protocols. Three typical examples of radial deformation

psychometric functions are shown in Figure 2. At low modulation amplitudes, infants show no consistent preference for either pattern, and the observer's performance is at chance level (50% correct). At moderate modulation amplitudes, performance increases above chance and, in general, reaches an upper asymptote of 100% correct. Overall, infant psychometric functions had high upper asymptotes (means = 0.98, 0.98, 0.99, and 0.98 for the 4-, 6-, 9-, and 12-month-old groups, respectively) and steep slopes (means = 20.3, 8.4, 28.3, and 14.8 for the 4-, 6-, 9-, and 12-month-old groups, respectively).

Maturation of Hyperacuity

As shown in Figure 3, both radial deformation and resolution thresholds were 1.1 to 1.2 logMAR (12–16 minutes arc; 6.7–8.9% D4 radius) at 4 months of age. Radial deformation thresholds improved rapidly to approximately 0.3 logMAR (2.0 min-

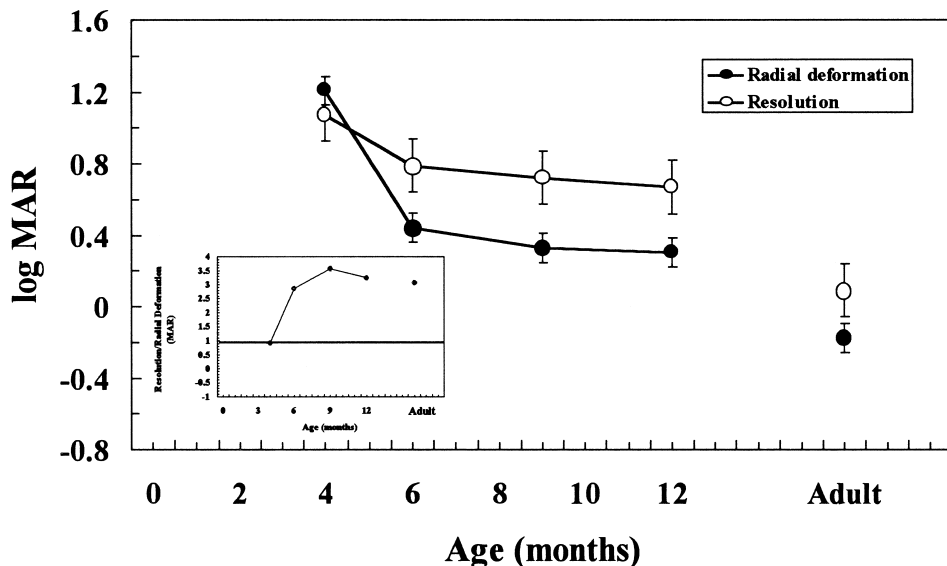


FIGURE 3. Mean radial deformation and resolution thresholds as a function of age. Vertical bars, ± 1 SEM. *Inset:* resolution/radial deformation threshold ratio as a function of age.

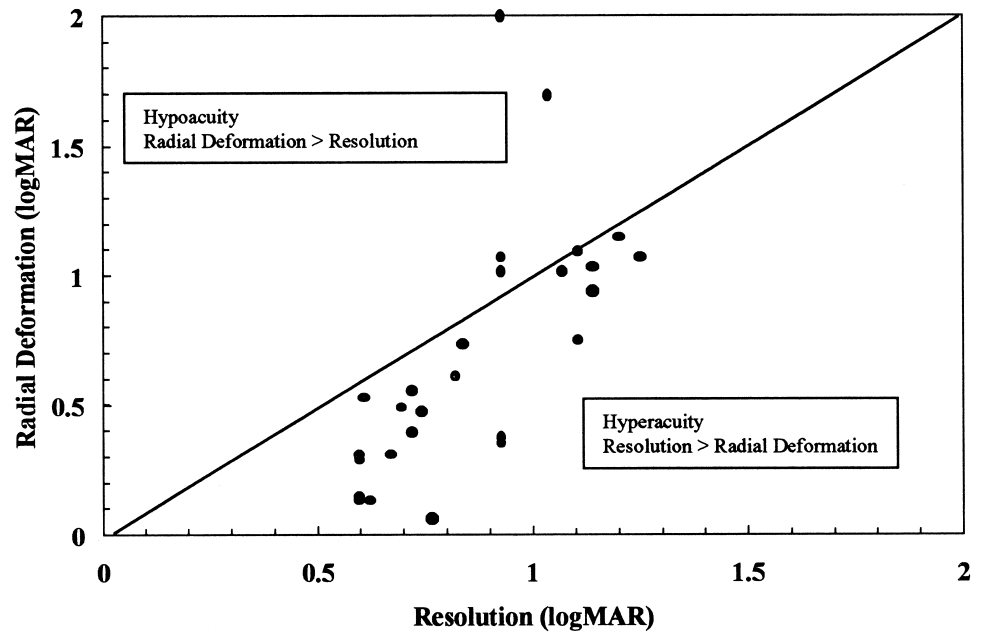


FIGURE 4. Individual radial deformation and resolution threshold data. The *diagonal line* indicates equal thresholds. Values that fall *below the diagonal* are consistent with hyperacuity (i.e., better performance on the radial deformation task). Values that fall *above the diagonal* are consistent with hypoacuity (i.e., better performance on the resolution task).

utes arc; 1.1% D4 radius) by 9 to 12 months of age. Although this represents 0.9 log unit improvement in the radial deformation thresholds, 12-month-old infants still remained 0.5 log unit poorer than adults' thresholds (-0.2 logMAR; 0.6 minutes arc; 0.33% D4 radius). Resolution thresholds improved more gradually to approximately 0.7 logMAR (5 minutes arc) by 9 to 12 months of age. With this 0.4 log unit improvement in resolution thresholds, the 12-month-old infants still remain 0.6 log unit poorer than mean adult resolution threshold (0.1 logMAR; 1.2 minutes arc).

Individual radial deformation and resolution threshold data are shown in Figure 4. The youngest infants (those with the poorest resolution acuities) do not show hyperacuity; that is, radial deformation and resolution thresholds are comparable and fall near or above the diagonal line that represents a resolution to radial deformation threshold ratio of 1:1. Older infants (those with better resolution acuities) consistently show hyperacuity; that is, radial deformation and resolution thresholds fall below the 1:1 ratio line.

Mean resolution/radial deformation threshold ratios are shown as a function of age in the inset of Figure 3. At 4 months of age, the ratio is slightly below 1.0; that is, resolution threshold is approximately 0.5 octave better than radial deformation threshold. At 6 months of age, the ratio is somewhat more mature, but shows further maturation between 6 and 9 months. Although both resolution and radial deformation thresholds continue to improve beyond 9 months of age, the resolution/radial deformation threshold ratios of 9- and 12-month-olds and of adults are comparable.

DISCUSSION

Infant sensitivity to radial deformation develops rapidly from 1.4 log unit poorer than adult levels at 4 months to within 0.5 log unit of adult level by 12 months. Maturation of this form of hyperacuity is extremely rapid between 4 and 6 months of age, improving by 0.75 log unit during these 2 months. Evaluation

of sensitivity to radial deformation is successful in more than 90% of infants aged 4 to 12 months, is not confounded by response to offset motion, and yields excellent discrimination performance.

A comparison with other data from recent studies of the maturation of hyperacuity is provided in Figure 5. Because the absolute level of hyperacuity depends on the spatial and temporal characteristics of the stimulus, only studies in which adult performance was reported under the same test conditions are included in the figure so that the data could be normalized. Although there is some scatter in the 4-month-old data despite normalization, the data from the present study generally agree with previous reports. However, at 6, 9, and 12 months, the data from the present study show substantially more mature hyperacuity than other studies have. As previously reported by Gwiazda et al.²⁵ and by Carkeet et al.,²⁶ it is clear that maturation is not complete by 12 months of age and that the maturation of hyperacuity continues beyond the first year of life.

There is some evidence that global form units like those reported by Gallant et al.^{27,28} in primate V4 may underlie sensitivity to the radial deformation used to measure hyperacuity in the present study. Units in this extrastriate area have large receptive fields and are optimally responsive to stimuli with circular structure. Thus, the radial deformation hyperacuity task used in the present study may reflect the maturation of higher visual areas that encode global object shape.²⁹ On the other hand, radial deformation thresholds are severely disrupted by strabismic amblyopia as are more standard offset detection measures of hyperacuity.²² Strabismic amblyopia is believed to have major effects in V1, including changes in ocular preference of cells in favor of the fixating eye and reduced binocularity.³⁰⁻³² Therefore, it is possible that the elevations in radial deformation threshold observed in amblyopia may not represent alterations in V4 function but, instead, may reflect changes in the V1 input to the extrastriate site.²² During infancy, then, the critical immaturity in hyperacuity

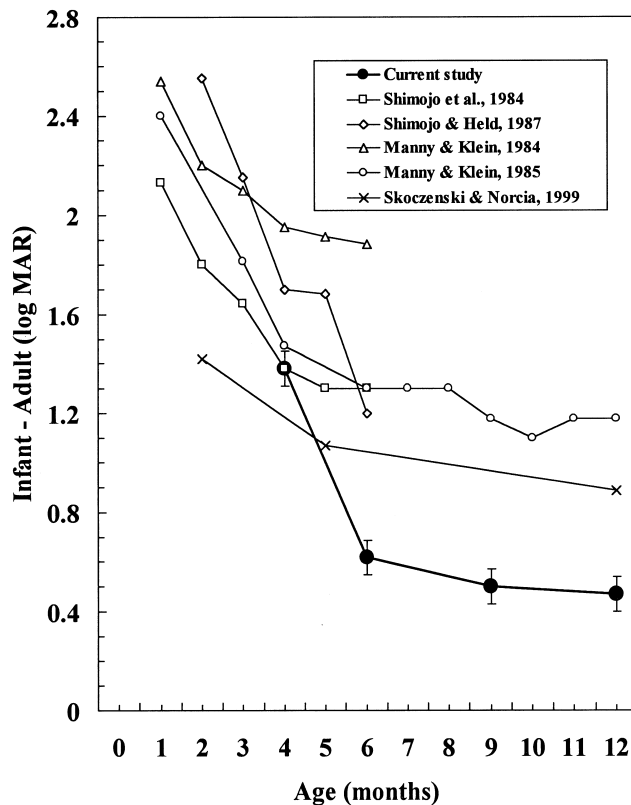


FIGURE 5. Comparison of data from the present study with data from recent studies of the maturation of hyperacuity in human infants. All thresholds are normalized relative to adult thresholds obtained with the same protocol used to measure infant hyperacuity in each study.

also may be in V1 even though an extrastriate area underlies performance on the radial modulation task.

Hyperacuity measured via radial deformation thresholds matures very rapidly between 4 and 6 months of age and continues to mature more slowly throughout infancy and into early childhood. Because adults with strabismic amblyopia show more profound impairment of hyperacuity than grating, the radial deformation protocol may provide a sensitive index for determining abnormalities in spatial vision in cases of infantile esotropia. Moreover, it may provide a better method than grating acuity for evaluating response to amblyopia therapy during infancy.

Acknowledgments

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