Abnormal Radial Deformation Hyperacuity in Children with Strabismic Amblyopia

Vidhya Subramanian,¹ Sarah E. Morale,¹ Yi-Zhong Wang,^{1,2} and Eileen E. Birch^{1,2}

PURPOSE. In infants and toddlers, letter acuity is not a useful option, and grating acuity may underestimate the depth of strabismic amblyopia. Here, as a first step to establish the effectiveness of the paradigm as a clinical test, we assessed if radial deformation hyperacuity, known to be severely disrupted in adults with strabismic amblyopia, could be a potential test to detect and monitor strabismic amblyopia in young children.

METHODS. Fifty-one strabismic children and 130 normal controls ages 3 to 17 years participated. Radial deformation hyperacuity with three different radial frequency (RF) patterns (1° radius 8 RF, 0.5° radius 8 RF, and 1° radius 16 RF), optotype acuity, and grating acuity were measured. For strabismic children, hyperacuity and grating acuity were identified as normal/amblyopic based on age-matched norms. The normal/abnormal classification was compared with amblyopia diagnosis by gold standard early treatment diabetic retinopathy study (ETDRS) optotype visual acuity.

RESULTS. The 0.5° radius 8 RF pattern had 83% sensitivity and 71% positive predictive value (PPV) for strabismic amblyopia. In comparison, the 1° radius 8 RF and 1° radius 16 RF patterns had poorer sensitivity (27%–12%) and PPV (57%–50%) for amblyopia, similar to grating acuity (sensitivity = 38%, PPV = 31%). Amblyopic deficits using the 0.5° radius 8 RF pattern were directly proportional to optotype visual acuity deficits.

CONCLUSIONS. The demonstrated feasibility of radial deformation stimuli for forced-choice preferential looking testing and the sensitivity and specificity of the small radius radial deformation hyperacuity stimulus for amblyopia support the potential to utilize this test to detect and monitor amblyopia in infants and preschool children. (*Invest Ophthalmol Vis Sci.* 2012;53:3303–3308) DOI:10.1167/iovs.11-8774

Reduced letter optotype visual acuity in an otherwise healthy eye is the hallmark of strabismic amblyopia. However, use of letter optotype visual acuity as an outcome measure in infants and children younger than 3 years is impractical. The current clinical standard for diagnosis and monitoring of strabismic amblyopia in infants and preschool children is fixation preference.¹ Two recent population studies have questioned the accuracy of fixation preference as a screening tool for amblyopia.^{2,3} Fixation preference does have

reasonable positive and negative predictive value in clinical cohorts with strabismus.^{4,5} Furthermore, fixation preference provides only a dichotomous outcome of amblyopic or nonamblyopic and does not provide a quantitative measure of severity of amblyopia for guiding treatment decisions or monitoring response to treatment.

Grating acuity, a quantitative measure of visual acuity that is easily measured in infants and preschool children, is highly correlated with letter optotype visual acuity but underestimates the severity of strabismic amblyopia.^{6,7} Hyperacuity tasks, on the other hand, are highly correlated with letter optotype visual acuity, and amblyopic hyperacuity deficits are nearly directly proportional to deficits in letter optotype visual acuity.^{8–10} Hence, adaptation of a hyperacuity test for infants and preschool children may yield a useful method for detection of strabismic amblyopia, assessment of the severity of amblyopia, and monitoring its response to treatment.

The radial deformation shape discrimination task, initially described by Wilkinson et al.,¹¹ measures the detection threshold for radial deformations of circular D4 (fourth derivative of Gaussian) contours, so-called radial frequency (RF) patterns. The threshold for detecting radial deformation is a hyperacuity, that is, a spatial discrimination that is substantially better than visual acuity.¹² It has been suggested that, to achieve the optimal performance, a global integration mechanism must be involved.^{11,13–15} The radial deformation task has been adapted to a forced-choice preferential looking paradigm and used to document the rapid improvement of hyperacuity during the first year of life.^{16,17} The rate of radial deformation hyperacuity maturation is similar to that reported with more traditional hyperacuity stimuli.¹⁶

Adults with strabismic amblyopia have severe deficits in radial deformation hyperacuity in the amblyopic eye compared to the fellow eye. These deficits are largely independent of spatial frequency characteristics of the circular contours (RF, contrast, and peak spatial frequency).¹³ However, while deficits in radial deformation hyperacuity were present in strabismic amblyopia across a wide range of RF stimuli, the most severe deficits were found at the two highest RFs, 8 and 10 cyc/360 deg. This latter finding may be related to the well-documented pronounced effect of crowding in strabismic amblyopia, a detrimental interference from flanking features or contours seen to impair visual acuity¹⁸ and vernier acuity.¹⁹

The aim of this study was to determine whether the radial deformation hyperacuity task could be used as a clinical tool to detect and monitor strabismic amblyopia in young children. The results of this research will be used to guide the choice of stimulus parameters for development of a preferential looking test to detect and monitor strabismic amblyopia in infants and preschool children. We have already demonstrated that radial deformation hyperacuity can be measured using forced-choice preferential looking in this age range.^{16,17} Here, we evaluated the sensitivity and specificity of the radial deformation shape discrimination task for strabismic amblyopia. Because there is no gold standard for strabismic amblyopia in children <3 years

From the ¹Retina Foundation of the Southwest, Dallas, Texas; and the ²Department of Ophthalmology, University of Texas Southwestern Medical Center, Dallas, Texas.

Supported by National Institutes of Health Grant EY05236 (EEB).

Submitted for publication October 10, 2011; revised January 16, March 18, and April 5, 2012; accepted April 10, 2012.

Disclosure: V. Subramanian, None; S.E. Morale, None; Y.-Z. Wang, None; E.E. Birch, None

Corresponding author: Vidhya Subramanian, Retina Foundation of the Southwest, 9900 North Central Expressway, Suite 400, Dallas, TX 75231-0920; vsubramanian@retinafoundation.org.

of age, we evaluated the sensitivity and specificity in strabismic children between the ages of 3 and 17 years using optotype visual acuity as the gold standard. In addition, we examined the relationship between hyperacuity deficits and optotype visual acuity deficits in amblyopic children in order to evaluate whether the hyperacuity task could be used to quantify severity of amblyopia and monitor response to treatment.

METHODS

Participants were 51 children between the age of 3 and 17 years with strabismus and no anisometropia (difference in spherical equivalent <1.00 diopters [D]). They were referred to the study by 18 Dallas-Fort Worth pediatric ophthalmologists. Fifty-two percent had amblyopia, defined as best-corrected letter optotype visual acuity of 20/40 or worse (≥ 0.3 logMAR) in the amblyopic eye and a difference of two lines (≥ 0.2 logMAR interocular difference) or more between the two eyes. One hundred thirty age-matched normal controls were included as a comparison group. None of the children had known developmental delay or concurrent ophthalmic or systemic diseases. None of the children were born preterm (≤ 36 weeks).

Informed consent was obtained from parents, as the children were younger than 18 years, before participation in the study. 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. The Retina Foundation of the Southwest is a Health Insurance Portability and Accountability Act (HIPAA)-exempt institution.

Hyperacuity, optotype acuity, and grating acuity were tested monocularly, using a different chart for each eye. Strabismic patients were tested with best optical correction.

Radial Deformation Hyperacuity

RF patterns were circular D4 contours, which could be radially deformed (Fig. 1). RF patterns were defined by peak spatial frequency (cyc/deg), which determined the thickness of the contour; mean radius (deg), which determined the size of the circle; and RF (the number of modulation cycles per 360 deg).²⁰ Radial deformation hyperacuity was evaluated using circular D4 contours with a peak spatial frequency of 3 cyc/deg, 1 deg radius, and RF = 8 (Fig. 1A). This stimulus was chosen because of a prior report that radial deformation hyperacuity was more severely affected when the circular contour frequency (the number of radial cyc/deg of unmodulated contour length) measured was ≥ 0.8 cyc/cl-deg.²⁰ This stimulus had a circular contour frequency of 1.3 cyc/cl-deg. In addition, we "crowded" RF patterns by increasing RF to 16 while keeping the radius constant at 1 deg (i.e., twice as many deformations along the same total contour length) (Fig. 1B) and by decreasing the radius to 0.5 deg while keeping the number of radial deformations constant (i.e., the same number of radial deformations along half the contour length) (Fig. 1C). These latter two radial deformation stimuli had a circular contour frequency of 2.6 cyc/cl-deg. Separate patient cohorts, enrolled sequentially, were used to test the three different hyperacuity tasks. Participants were grouped by age: 3–4, 5–6, 7–8, 9–10, and 11–17 years. The number of children tested with each of the three hyperacuity tasks by age group is provided in Table 1. Some children were tested with more than one hyperacuity task; but, because the tasks were evaluated sequentially, they were in different age groups when they were tested with different hyperacuity tasks, and differences in thresholds for the tasks could not be compared within individuals. For example, of the 27 amblyopic children, 12 were tested with one hyperacuity task, 13 were tested with two hyperacuity tasks, and 2 were tested with all three hyperacuity tasks, for a total of 44 tests.

Radial deformation hyperacuity was measured using spatial four-alternative forced-choice charts. Each chart consisted of 16 groups of four RF patterns, three unmodulated and one modulated (deformed)

FIGURE 1. Examples of radial deformation stimuli used in the study. (A) 1 deg radius 8 RF radial deformation stimulus, (B) 1 deg radius 16 RF radial deformation stimulus, and (C) 0.5 deg radius 8 RF radial deformation stimulus.

(Fig. 2A). The subject viewed the charts at 40 cm. The subject's task was to indicate the deformed RF pattern from among four RF patterns in each group, of which three were perfectly circular patterns. A masking sheet with a rectangular presentation window (Fig. 2B) was used to present only one group at a time. From top-left to bottom-right groups, the % radial modulation amplitudes were 10, 6.3, 4.0, 2.8, 2.0, 1.4, 1.0, 0.79, 0.63, 0.50, 0.40, 0.32, 0.25, 0.20, 0.16, and 0.13. When converted to logMAR, these correspond to 0.2 logMAR steps for the initial five stimulus sets (for a 1 deg radius stimulus: 0.8, 0.6, 0.4, 0.2, and 0.0 logMAR) and 0.1 logMAR steps for subsequent 11 steps (for a 1 deg radius stimulus: -0.1 , -0.2 , -0.3 , -0.4 , -0.5 , -0.6 , -0.7 , -0.8 , -0.9 , -1.0 , and -1.1 logMAR). The smallest amplitude of radial modulation detected before two consecutive errors was scored as the hyperacuity threshold.

Optotype acuity was measured using the crowded single letter protocol in the electronic-ETDRS (E-ETDRS) format^{21,22} and served as the gold standard. Viewing distance was 3 m. Grating acuity was measured using a two-alternative forced-choice format with Teller acuity cards^{23–25} (viewing distance 57 cm) to provide a comparison with radial deformation hyperacuity.

Statistical Analysis

The developmental course of normative hyperacuity and grating acuity thresholds was modeled using a two-segment function.¹⁷ The first

TABLE 1. Number of Children Tested in Each of the Three Hyperacuity Tasks by Age Group

Hyperacuity Task	3 to 4 (y)	5 to 6 (y)	7 to 8 (y)	9 to 10 (y)	11 y and Older
1 deg radius 8 RF	35 (1 A, 9 NA, 25 C)	39 (5 A, 4 NA, 30 C)	27 (2 A, 2 NA, 23 C)	18 (3 A, 0 NA, 15 C)	24 (4 A, 1 NA, 19 C)
1 deg radius 16 RF	18 (4 A, 6 NA, 8 C)	25 (4 A, 3 NA, 18 C)	24 (3 A, 5 NA, 16 C)	14 (2 A, 1 NA, 11 C)	23 (4 A, 2 NA, 17 C)
0.5 deg radius 8 RF	19 (4 A, 7 NA, 8 C)	19 (3 A, 1 NA, 15 C)	19 (2 A, 3 NA, 14 C)	13 (1 A, 1 NA, 11 C)	20 (2 A, 2 NA, 16 C)

The breakdown of the number of children tested in the amblyopic group (A), nonamblyopic group (NA), and normal control group (C) in the different age groups for the three hyperacuity tasks is provided within parentheses.

segment was an exponential growth curve, which captured the initial rapid development of visual function. The second segment was a horizontal line to describe the absence of further changes in threshold once maturation is complete. Mathematically, this developmental course was defined by the following equations:

$$y = \begin{cases} a + a_1 [e^{-b(x-c)} - 1] & x < c \\ ax & x \geq c \end{cases}$$

where x is age and y is the measurement of threshold. The model has four parameters: a , a_1 , b , and c , where a is the stable, mature threshold level and c is the age at which the threshold reaches the stable, mature

level. A search grid for the four parameters was formed for fitting, using a criterion of minimal root mean square error.

For sensitivity and specificity analyses, each monocular hyperacuity and grating acuity threshold from strabismic patients was compared with the control range of scores for the same age group. For sensitivity and specificity analyses, patient thresholds that fell within the control range for the same age group were classified as “normal,” and patient thresholds that fell below the lower limit of the control range for the same age group were classified as “abnormal.” Sensitivity of the radial deformation hyperacuity for amblyopia (percentage correctly identified as having amblyopia) and specificity (percentage correctly identified as being nonamblyopic) were calculated from 2×2 contingency tables. Positive predictive value (PPV, probability of being truly amblyopic given a positive result) and negative predictive value (NPV, probability of being truly nonamblyopic given a negative result) were also calculated. For comparison, sensitivity, specificity, PPV, and NPV were also calculated for grating acuity. The sensitivity, specificity, and the predictive values are presented along with their 95% confidence interval (CI).

RESULTS

Normative Radial Deformation Hyperacuity Data

Figure 3 plots the mean radial deformation hyperacuity data for the three different RF patterns and the grating acuity in logMAR as a function of age. For all three RF patterns, radial deformation hyperacuity exceeded grating acuity by ≥ 0.3 logMAR in all age groups. Modeling the individual data with two-segment growth curves, radial deformation hyperacuity was found to reach a mature, stable level at 13 years of age for the 1 deg radius 8 RF pattern but continued to improve through at least 17 years of age for the two crowded RF patterns (1 deg radius 16 RF and 0.5 deg radius 8 RF). In contrast, grating acuity matured early, reaching a plateau of -0.1 logMAR by 9 years of age.

A two-way ANOVA was carried out to compare the normative data, from the right eyes of normal control children, for the three RF patterns as a function of age group. The mean radial deformation hyperacuity was found to be statistically significantly different among the three RF patterns ($F = 20.81$; $P < 0.001$) and across age groups ($F = 24.31$; $P < 0.001$). In addition, a significant interaction effect ($F = 2.16$; $P = 0.03$) between age group and hyperacuity task was observed. The significant interaction primarily reflects the poorer thresholds of children tested at 3–4 years of age with the 0.5 deg radius 8 RF and 1.0 deg 16 RF patterns compared with 1 deg radius 8 RF pattern ($P < 0.05$ for both comparisons) and the later age at which thresholds reach visual maturity for the 0.5 deg radius 8 RF and 1.0 deg 16 RF patterns compared with 1 deg radius 8 RF pattern.

Sensitivity, Specificity, and Predictive Value of Radial Deformation Hyperacuity for Strabismic Amblyopia

Sensitivity, specificity, PPV, and NPV for each of the three RF patterns, along with their 95% CIs, are summarized in Table 2.

FIGURE 2. (A) Sample of radial deformation hyperacuity chart (1° radius 16 RF stimulus). (B) Example of the masking sheet with the presentation window.

FIGURE 3. Box plots of the normative data, which provides the mean (black dots), median (horizontal line within the box), lower quartile (25th percentile), upper quartile (75th percentile), and range (whiskers) for grating acuity and the three hyperacuity tasks.

Neither of the 1 deg radius patterns (RF 8 and RF 16) had high sensitivity or PPV for strabismic amblyopia, although both had reasonable specificity and NPV. In contrast, the 0.5 deg RF8 pattern had 83% sensitivity, 85% specificity, and 71% PPV.

In comparison, only one third of 13 children (out of 37 children tested) who were identified as amblyopic by E-ETDRS letter acuity were also identified as amblyopic by grating acuity. Overall, grating acuity had low sensitivity of 38% (95% CI: 15%–68%) with a PPV = 31% (95% CI: 12%–58%) and modest specificity of 73% (95% CI: 56%–85%) with a NPV of 78% (95% CI: 61%–90%).

Radial Deformation Hyperacuity and Grating Acuity versus Gold Standard E-ETDRS Visual Acuity in the Patient Population

Figures 4A, 4B, 4C, and 4D provide scatterplots along with the best-fit lines to illustrate the relationship between optotype acuity and grating acuity and between optotype acuity and the three RF patterns.

The 1 deg radius 8 RF radial deformation hyperacuity was not significantly correlated with optotype acuity among amblyopic patients (Spearman $r = 0.13$, $P = 0.67$) or among all participants (Spearman $r = -0.13$, $P = 0.44$). However, the two crowded hyperacuity stimuli showed significant correlations with optotype acuity among amblyopic participants (1 deg radius 16 RF stimuli: Spearman $r = 0.59$, $P = 0.013$; 0.5 deg radius 8 RF stimuli: Spearman $r = 0.83$, $P = 0.001$) and among all participants (1 deg radius 16 RF stimuli: Spearman $r = 0.53$, $P < 0.001$; 0.5 deg radius 8 RF stimuli: Spearman $r = 0.72$, $P < 0.001$). The best-fit line for the 0.5 deg radius 8 RF hyperacuity task was steeper (slope = 1.42) than for the other two hyperacuity tasks (1 deg radius 8 RF slope = 0.30; 1 deg radius 16 RF slope = 0.72); that is, loss of hyperacuity for 0.5 deg 8 RF patterns was proportional to or greater than loss of optotype acuity in strabismic amblyopia.

DISCUSSION

This evaluation of hyperacuity test validity in a cohort old enough to complete optotype acuity testing demonstrated good sensitivity and excellent specificity for strabismic amblyopia for 0.5 deg 8 RF patterns. This small radius radial deformation hyperacuity had better sensitivity and PPV in identifying strabismic amblyopia compared to grating acuity and large radius radial deformation hyperacuity. In addition, the small radius radial deformation hyperacuity deficits were proportional to optotype visual acuity deficits.

Previous studies have reported hyperacuity maturation and normative data during infancy and early childhood.^{26,27} Wang et al.¹⁷ report the development and course of global hyperacuity from infancy to aging. The normative data presented in this study for early childhood through teenage years agrees well with these previous reports. Interestingly, hyperacuity was found to be similar for the two RF patterns with the same contour frequency (1 deg radius 16 RF and 0.5 deg radius 8 RF patterns) across the different age groups, which has been reported previously.^{15,17} However, the normative data obtained from the 1 deg radius 8 RF pattern, with a lower contour frequency, was different from the other two stimuli. These results also are consistent with the hypothesis that radial deformation hyperacuity is determined by contour frequency.¹⁵

There has been only one previous report of a hyperacuity test intended for detection and monitoring of amblyopia in infants and preterm children.²⁸ Similar to the current study, they assessed the sensitivity and specificity of hyperacuity to amblyopia, using optotype acuity as the gold standard, in a cohort of children ≥ 3 years of age. The results were similar to the present study. Namely, vernier acuity was 81% sensitive in identifying amblyopia with 73% specificity. Grating acuity yielded a much lower sensitivity of 44%, but a comparable specificity of 93%.

The finding here that a small radius, crowded RF pattern has good sensitivity and excellent specificity for strabismic

TABLE 2. Sensitivity, Specificity, and Predictive Value of Radial Deformation Hyperacuity for Strabismic Amblyopia

	Sensitivity (95% CI)	Specificity (95% CI)	PPV (95% CI)	NPV (95% CI)
1 deg radius 8 RF	27% (8–55)	90% (73–97)	57% (20–88)	72% (54–84)
1 deg radius 16 RF	12% (2–37)	94% (77–98)	50% (9–90)	66% (50–79)
0.5 deg radius 8 RF	83% (50–97)	85% (65–95)	71% (42–90)	92% (72–98)

amblyopia compared to the large radius, crowded RF pattern with the same contour frequency suggests that crowding might not be an underlying factor resulting in the hyperacuity deficit. This finding is consistent with data from other radial deformation hyperacuity studies that have shown a high degree of scale invariance in strabismic amblyopia.^{13,20} Radial deformation hyperacuity has been reported to be constant across increasing RF, for a given radius, in individuals with strabismic amblyopia.¹³

It is generally considered that V1 is the predominant site for crowding, with some possible involvement downstream from V1.²⁹ However, the global summation involved in radial deformation hyperacuity is likely to occur within V4.^{11,30} Our data support the V4 locus hypothesis. If crowding was the predominant factor in the amblyopic hyperacuity deficits observed, similar hyperacuity deficits should have been observed with both the 0.5 deg radius 8 RF pattern and 1 deg radius 16 RF pattern, indicating a V1 locus. However, the 1 deg 16 RF pattern yielded less amblyopic deficit than the 0.5 deg radius 8 RF pattern, suggesting that crowding might not be the underlying mechanism, consistent with the V4 locus.

The small 0.5 deg radius stimulus serves to limit testing to the central 1 deg of fovea, and its higher sensitivity to strabismic amblyopia compared with larger radius patterns may reflect the greater effect of strabismic amblyopia on foveal than extrafoveal vision. Consistent with this hypothesis is a report by Mayer et al.³¹ that small field (0.5 deg radius) grating acuity was affected to a greater extent than large field grating

acuity in amblyopia and that small field grating acuity deficits were more similar to optotype visual acuity deficits.

Whether the results from children ages 3 to 17 years presented here can be generalized to infants and preschool children was not addressed in the present study. There is no gold standard for the infant-preschool age group, so it is not possible to determine whether an infant or child has amblyopia with certainty. Thus, to evaluate and validate whether a radial deformation hyperacuity task may be sensitive to strabismic amblyopia in infants and preschool children, the study cohort must be composed of children who are old enough to complete a standardized visual acuity test that can establish the formal diagnosis of amblyopia. Prior studies have already demonstrated that the radial deformation hyperacuity task can be used to assess hyperacuity of normal infants in a forced-choice preferential looking paradigm,^{16,17} although hyperacuity stimuli with radii as small as 0.5 deg have not yet been studied.

This study evaluated the clinical effectiveness of radial deformation hyperacuity in detecting strabismic amblyopia in preschool and school-aged children. Moreover, it was able to identify a small radius RF pattern as the most efficient test target among different types of radial deformation hyperacuity stimuli. The strong correlation and direct proportionality of the hyperacuity deficits, when measured with the small radius stimulus, and optotype deficits in amblyopic children support the utility of small radius radial deformation hyperacuity in quantifying the severity of amblyopia and monitoring the course of amblyopia treatment. Taken together, these results

FIGURE 4. Scatterplots of (A) grating acuity versus optotype acuity (slope of the best-fit line = 0.39); (B) 1 degree radius 8 RF radial deformation hyperacuity versus optotype acuity (slope of the best-fit line = 0.30); (C) 1 degree radius 16 RF radial deformation versus optotype acuity (slope of the best-fit line = 0.72); and (D) 0.5 degree radius 8 RF hyperacuity versus optotype acuity (slope of the best-fit line = 1.42).

suggest that a small radius radial deformation hyperacuity task has good potential as a forced-choice preferential looking test to detect and monitor amblyopia in infants and preschool children. However, this paradigm has yet to be tested in infants and toddlers.

References

1. American Academy of Ophthalmology Pediatric Ophthalmology/Strabismus Panel. *Preferred Practice Pattern Guidelines. Amblyopia*. San Francisco, CA: American Academy of Ophthalmology; 2007.
2. Friedman DS, Katz J, Repka MX, et al. Lack of concordance between fixation preference and HOTV optotype visual acuity in preschool children: the Baltimore Pediatric Eye Disease Study. *Ophthalmology*. 2008;115:1796-1799.
3. Cotter SA, Tarczy-Hornoch K, Song E, et al. Fixation preference and visual acuity testing in a population-based cohort of preschool children with amblyopia risk factors. *Ophthalmology*. 2009;116:145-153.
4. Procianny L, Procianny E. The accuracy of binocular fixation preference for the diagnosis of strabismic amblyopia. *J Am Assoc Pediatr Ophthalmol Strabismus*. 2010;14:205-210.
5. Kothari M, Bhaskare A, Mete D, Toshniwal S, Doshi P, Kaul S. Evaluation of central, steady, maintained fixation grading for predicting inter-eye visual acuity difference to diagnose and treat amblyopia in strabismic patients. *Indian J Ophthalmol*. 2009;57:281-284.
6. Mayer DL, Fulton AB, Rodier D. Grating and recognition acuities of pediatric patients. *Ophthalmology*. 1984;91:947-953.
7. Drover JR, Wyatt LM, Stager DR, Birch EE. The teller acuity cards are effective in detecting amblyopia. *Optom Vis Sci*. 2009;86:755-759.
8. McKee SP, Levi DM, Movshon JA. The pattern of visual deficits in amblyopia. *J Vis*. 2003;3:380-405.
9. Levi DM, Klein S. Hyperacuity and amblyopia. *Nature*. 1982;298:268-270.
10. Levi DM, Klein S. Differences in vernier discrimination for grating between strabismic and anisometropic amblyopes. *Invest Ophthalmol Vis Sci*. 1982;23:398-407.
11. Wilkinson F, Wilson HR, Habak C. Detection and recognition of radial frequency patterns. *Vision Res*. 1998;38:3555-3568.
12. Westheimer G. Visual acuity and hyperacuity. In: Bass M, ed. *Handbook of Optics, Vol. III: Vision and Vision Optics*. New York, NY: McGraw-Hill; 2009:4.1-4.12.
13. Hess RF, Wang YZ, Demanins R, Wilkinson F, Wilson HR. A deficit in strabismic amblyopia for global shape detection. *Vision Res*. 1999;39:901-914.
14. Wang YZ, Hess RF. Contributions of local orientation and position features to shape integration. *Vision Res*. 2005;45:1375-1383.
15. Jeffrey BG, Wang YZ, Birch EE. Circular contour frequency in shape discrimination. *Vision Res*. 2002;42:2773-2779.
16. Birch EE, Swanson WH, Wang YZ. Infant hyperacuity for radial deformation. *Invest Ophthalmol Vis Sci*. 2000;41:3410-3414.
17. Wang YZ, Morale SE, Cousins R, Birch EE. Course of development of global hyperacuity over lifespan. *Optom Vis Sci*. 2009;86:695-700.
18. Flom MC, Weymouth FW, Kahneman D. Visual resolution and contour interaction. *J Opt Soc Am*. 1963;53:1026-1032.
19. Levi DM, Klein SA. Vernier acuity, crowding and amblyopia. *Vision Res*. 1985;25:979-991.
20. Jeffrey BG, Wang YZ, Birch EE. Altered global shape discrimination in deprivation amblyopia. *Vision Res*. 2004;44:167-177.
21. Beck RW, Moke PS, Turpin AH, et al. A computerized method of visual acuity testing: adaptation of the early treatment of diabetic retinopathy study testing protocol. *Am J Ophthalmol*. 2003;135:194-205.
22. Moke PS, Turpin AH, Beck RW, et al. Computerized method of visual acuity testing: adaptation of the amblyopia treatment study visual acuity testing protocol. *Am J Ophthalmol*. 2001;132:903-909.
23. Mayer DL, Fulton AB. Preferential looking grating acuities of infants at risk of amblyopia. *Trans Ophthalmol Soc UK*. 1985;104(Pt 8):903-911.
24. Dobson V. Clinical applications of preferential looking measures of visual acuity. *Behav Brain Res*. 1983;10:25-38.
25. Birch EE, Hale LA. Criteria for monocular acuity deficit in infancy and early childhood. *Invest Ophthalmol Vis Sci*. 1988;29:636-643.
26. Manny RE, Klein SA. The development of vernier acuity in infants. *Curr Eye Res*. 1984;3:453-462.
27. Shimojo S, Birch EE, Gwiazda J, Held R. Development of vernier acuity in infants. *Vision Res*. 1984;24:721-728.
28. Drover JR, Morale SE, Wang YZ, Stager DR Sr, Birch EE. Vernier acuity cards: examination of development and screening validity. *Optom Vis Sci*. 2010;87:E806-E812.
29. Levi DM. Crowding—an essential bottleneck for object recognition: a mini-review. *Vision Res*. 2008;48:635-654.
30. Wilkinson F, James TW, Wilson HR, Gati JS, Menon RS, Goodale MA. An fMRI study of the selective activation of human extrastriate form vision areas by radial and concentric gratings. *Curr Biol*. 2000;10:1455-1458.
31. Mayer DL. Acuity of amblyopic children for small field gratings and recognition stimuli. *Invest Ophthalmol Vis Sci*. 1986;27:1148-1153.