

The Ohio Contrast Cards: Visual Performance in a Pediatric Low-vision Site

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SIGNIFICANCE: This report describes the first clinical use of the Ohio Contrast Cards, a new test that measures the maximum spatial contrast sensitivity of low-vision patients who cannot recognize and identify optotypes and for whom the spatial frequency of maximum contrast sensitivity is unknown.

PURPOSE: To compare measurements of the Ohio Contrast Cards to measurements of three other vision tests and a vision-related quality-of-life questionnaire obtained on partially sighted students at Ohio State School for the Blind.

METHODS: The Ohio Contrast Cards show printed square-wave gratings at very low spatial frequency (0.15 cycle/degree). The patient looks to the left/right side of the card containing the grating. Twenty-five students (13 to 20 years old) provided four measures of visual performance: two grating card tests (the Ohio Contrast Cards and the Teller Acuity Cards) and two letter charts (the Pelli-Robson contrast chart and the Bailey-Lovie acuity chart). Spatial contrast sensitivity functions were modeled using constraints from the grating data. The Impact of Vision Impairment on Children questionnaire measured vision-related quality of life.

RESULTS: Ohio Contrast Card contrast sensitivity was always less than 0.19 \log_{10} units below the maximum possible contrast sensitivity predicted by the model; average Pelli-Robson letter contrast sensitivity was near the model prediction, but 0.516 \log_{10} units below the maximum. Letter acuity was 0.336 logMAR below the grating acuity results. The model estimated the best testing distance in meters for optimum Pelli-Robson contrast sensitivity from the Bailey-Lovie acuity as distance = 1.5 – logMAR for low-vision patients. Of the four vision tests, only Ohio Contrast Card contrast sensitivity was independently and statistically significantly correlated with students' quality of life.

CONCLUSIONS: The Ohio Contrast Cards combine a grating stimulus, a looking indicator behavior, and contrast sensitivity measurement. They show promise for the clinical objective of advising the patient and his/her caregivers about the success the patient is likely to enjoy in tasks of everyday life.

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The invention in the mid-1980s of the Teller Acuity Card test¹ profoundly changed the assessment of visual acuity in the clinic because for the first time it was possible to measure visual acuity on infants, patients with multiple disabilities, and others who cannot recognize and identify the optotypes on an eye chart. However, visual acuity does not give the clinician a complete picture of the visual capabilities of a patient because many aspects of everyday life, such as social interactions and mobility, are limited by visual contrast sensitivity rather than acuity.^{2,3} At about the same time, the problem of measuring a patient's overall contrast sensitivity was elegantly solved for most capable and healthy children and adults by the invention of the Pelli-Robson chart,⁴ a letter chart containing very large letters of variable contrast. However, there is currently no well-established, convenient clinical test of contrast sensitivity for use on uninstruable patients and those who cannot be tested using a letter or other optotype eye chart. This project was designed to take the first steps toward establishing a card-based test of grating contrast sensitivity.

The measurement of contrast sensitivity is more complicated than the measurement of visual acuity. Grating acuity can be measured easily by finding the highest spatial frequency black-and-white

grating that the patient can discriminate from a gray stimulus whose luminance is matched to the space-averaged luminance of the grating. Similarly, letter acuity can be measured by finding the smallest letters that the patient can read at 100% contrast. These are simple measurements because the gratings or letters vary along only one stimulus continuum, that is, spatial frequency or letter size. By comparison, a patient's contrast sensitivity (the reciprocal of the minimum value of contrast the patient can detect) is not a unitary parameter because it always depends on spatial frequency. The relation between grating contrast sensitivity and spatial frequency, which is described using the contrast sensitivity function (blue diamonds in Fig. 1A), is known to vary with age and disease.² For example, the visually normal adult is most sensitive to contrast at around three cycles per degree of visual angle (cy/deg), a spatial frequency that is beyond the visual acuity limit of infants younger than approximately 6 months (Fig. 1A) and of many patients with visual disorders (Fig. 1B).

The Pelli-Robson chart⁴ solves the problem of measuring a patient's overall contrast sensitivity by using letters whose main spatial frequency (Fourier) components are near the patient's presumed contrast sensitivity peak. The letter-identification

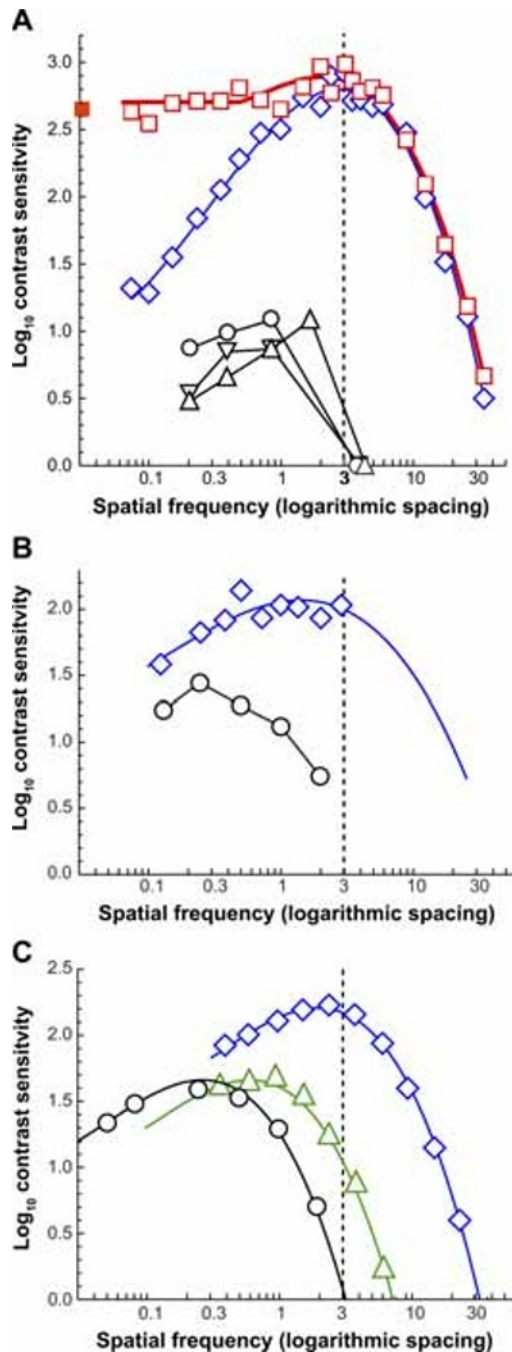


FIGURE 1. Contrast sensitivity functions on healthy adults, infants, and patients. (A) Adult data (19×24 -degree stimuli),⁵ central fixation, continuous viewing. Blue diamonds: sine-wave stimuli; red squares: square-wave stimuli; left-hand solid red square, edge; black symbols: 3-month-olds (15-degree stimuli).⁶ (B) 40-Degree sine-wave stimuli, free fixation. Blue diamonds and curve: healthy adult data and curve extrapolated by those authors;⁷ black circles: a patient with hereditary optic atrophy.⁸ (C) “Full field” sine-wave stimuli.⁹ Blue diamonds healthy adults. Black circles (subject K) and green triangles (subject O), patients with Stargardt disease. The curve fitted to the normal data was transposed in two dimensions to fit the patient data. A sine-wave target at 3 cy/deg (vertical dashed lines in all panels) would do a good job of estimating the maximum sensitivity of normal adults, but would underestimate the contrast sensitivity of the infants in (A), the optic atrophy patient in (B), and the patients with Stargardt disease in (C).

task is natural for many patients, and the Pelli-Robson chart is well designed to be used along with the Bailey-Lovie logMAR chart¹⁰ or other letter chart of visual acuity. At a testing distance of 3 m, the major Fourier components of the Pelli-Robson letters fall near 2.6 cy/deg, so the measured contrast sensitivity is approximately the best the visually normal patient can achieve. Pelli et al.⁴ suggest that the testing distance should be adjusted for the visual capabilities of low-vision patients, to allow a corresponding measure of their maximum possible contrast sensitivity. Because it is so easy to use and because of the large literature establishing its validity and reliability,^{11–13} the Pelli-Robson chart has enjoyed great success in the clinic. However, the Pelli-Robson chart requires that the patient be able to recognize and identify letters, and it requires that the shape of the contrast sensitivity function be known well enough for the clinician to adjust the testing distance to place the letters near the maximum of the contrast sensitivity function. These two requirements are often not met in a low-vision setting, where patients may never have learned to read visually presented letters fluently and where the maximum of the contrast sensitivity function may not be even approximately known.

In an effort to overcome these challenges, we designed the Ohio Contrast Cards for use with low-vision patients, and this project was planned to investigate their clinical utility and concurrent validity. We compared the contrast sensitivity and visual acuity of a group of partially sighted students at the Ohio State School for the Blind, using the Ohio Contrast Cards and three other well-validated clinical tests: the Teller Acuity Cards and two letter charts, the Bailey-Lovie acuity chart¹⁰ and the Pelli-Robson contrast sensitivity chart.⁴ We also assessed the impact of each student's vision on his/her everyday life using the Impact of Vision Impairment on Children (IVI_C) quality-of-life questionnaire,¹⁴ a well-validated instrument that was designed for use on children from 8 to 18 years old with visual impairment¹⁵ because the strong association between contrast sensitivity and visual function in everyday life is one of the main reasons for measuring contrast sensitivity clinically.^{2,16}

METHODS

Subjects

Participants were partially sighted students at the Ohio State School for the Blind. There were 18 full-time Ohio State School for the Blind students (6 female students; 14 white, 2 African Americans, 1 Asian), aged 13 to 20 years (mean, 16.1 [SD, 2.2] years), and 8 summer students (2 female students; 7 whites, 1 Asian), aged 10 to 17 years (mean, 12.9 [SD, 2.6] years), who attended regular public schools and enrolled in special programs at Ohio State School for the Blind (see Appendix A, available at <http://links.lww.com/OPX/A302>). The prospective Ohio State School for the Blind participants were identified from school records and were recruited by mail, whereas the summer students were recruited in person during registration for the summer program. Students younger than 18 years, whose guardians granted permission, participated after providing their own informed assent. Students older than 18 years were recruited in person and provided their own informed consent. Each student received a \$5 gift card after participating. The protocol for the study was approved by the Ohio State University Institutional Review Board and followed the tenets of the Declaration of Helsinki.

All students were partially sighted and qualified for enrollment in the Ohio State School for the Blind full time or summer program because of their low vision. All full-time students had corrected visual acuity (listed on their school records) of 0.78 or worse in their better eye (mean, 1.41 [SD, 0.52]). Three full-time students and four summer students had no measurable vision in one eye.

The Ohio Contrast Cards

For the Ohio Contrast Cards contrast sensitivity test, we chose a very low spatial frequency square wave (Fig. 2) because human contrast sensitivity, when measured with square-wave gratings, is empirically high and constant over a wide range of very low spatial frequencies.^{5,17-19} Therefore, the visibility of a square-wave grating does not depend very much on spatial frequency over this range (red squares in Fig. 1A), and it is much closer to the peak value of the contrast sensitivity function than what is reported for sine wave stimuli (compare red squares and blue diamonds in Fig. 1A, which we show because those authors also used large stimuli and unlimited viewing time; see also Carney et al.²⁰ and Watson and Ahumada²¹ Fig. 14). The red curve in Fig. 1A was predicted by the standard model of contrast detection^{20,21} applied to square waves of constant area, fitted to the square-wave data in Fig. 1A by transposing it rigidly relative to log axes to minimize the sum of squared residuals. The model is described below.

We chose a grating for the Ohio Contrast Cards rather than a single edge (red square in Fig. 1A) because it is visually distinctive, because it presents multiple edges for possible detection, and because we wanted to take advantage of the spacing of the discrete harmonics of a periodic stimulus. We chose a horizontal grating because most eye movement disorders affect horizontal more than vertical eye movements. We chose a three-cycle grating to approximate the 2.5 cycles per letter of the Sloan E,²² while maintaining constant space-average luminance.

We placed the gratings on cards of the same dimensions (55.5 × 25.5 cm) and approximately the same overall reflectance (50%) as the Teller Acuity Cards²³ to facilitate the use of the two tests in tandem, using the same “seen/not seen” decision by the examiner. The Ohio Contrast Cards are gray, and each contains a 22 × 20-cm horizontal square-wave grating on one side of its face (Fig. 2). The grating has a fixed spatial frequency of one cycle per 6.7 cm (at our testing distance of 57 cm, this is 0.15 cy/deg, corresponding to 20/4000 Snellen). The grating is in sine phase, with three complete cycles of light and dark bars. The near end of the grating starts 6 cm from the 3-mm peephole in the middle of the

card, and the far end of the grating extended to the edge of the card. The space-average reflectance of the gratings is 50%. Contrast values for the stripes range from 96% to 1% contrast in 0.15 log₁₀ unit steps. This progression of half-octave steps is similar to the Pelli-Robson chart.

To acknowledge the longtime support of our academic institution, we call them the “Ohio Contrast Cards” (Fig. 2).

The prototype Ohio Contrast Cards used in this project were printed onto matte polypropylene adhesive film by a large-format ink-jet printer (HP Z3200ps) and mounted on lightweight Sintra PVC cards (professionally made versions of the Ohio Contrast Cards are available from Precision-Vision, Inc., Woodstock, IL). The reflectance, contrast, and spatial frequency values of the cards corresponded closely to the parameters listed previously and were calibrated using a SpectraScan 6700 photometer (Photo Research, North Syracuse, NY).

Other Stimuli

The other three clinical tests of visual acuity and contrast sensitivity were conducted using commercially available stimuli. These were the Bailey-Lovie Chart (National Vision Research Institute of Australia, prepared by the Multimedia Center, School of Optometry, Berkeley, CA), the Pelli-Robson chart (Metropia, Ltd, UK, distributed by Clement Clarke International Ltd., Harlow, UK), and the Teller Acuity Cards (University of Washington, manufactured and distributed by VisTech Inc, Dayton, OH).

All four tests were printed materials, which were illuminated by two 18-W/950-lumen compact fluorescent flood lamps positioned behind the subject at a distance of 1.5 m from the white charts and 1.07 m from the gray cards. The typical luminance was 338 cd/m² for the gray cards. The luminances of the charts were 432 cd/m² at the 1-m test distance and 350 cd/m² at the 2-m distance. These were sufficient to place both infants and adults into a regimen where further increases in luminance do not produce improvements in visual acuity for infants or adults.²⁴

The IVI_C questions were from the Centre for Eye Research Australia¹⁵ (http://www.cera.org.au/pro-questionnaires/#ivi_c) and are listed in Appendix B, available at <http://links.lww.com/OPX/A303>.

Vision Test Procedures

A balanced Latin-square pseudorandomization table determined the order of the vision tests for each session. The students with two partially sighted eyes were tested with each eye, using

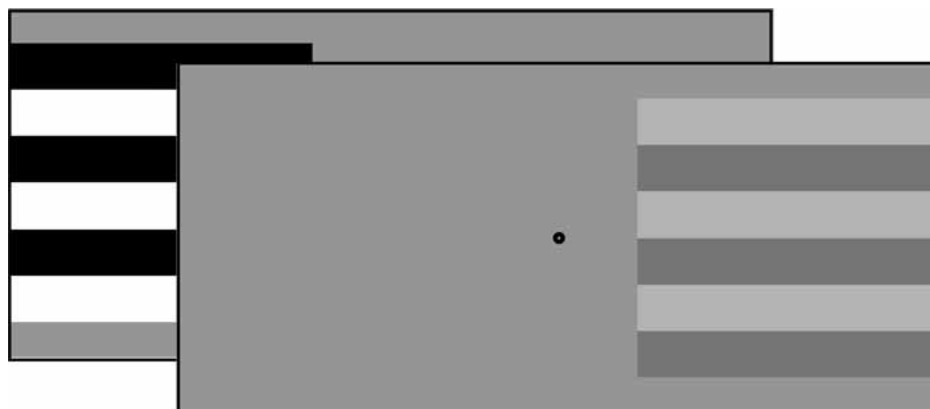


FIGURE 2. Two examples of the Ohio Contrast Cards. The dot in the center of the lower contrast card is a peephole.

an eye patch on the fellow eye, viewing with the right eye first. Students with only one partially sighted eye were tested with that eye only, with an eye patch on the fellow (blind) eye. Students wore their habitual spectacle correction. Vision testing was performed by coauthor G.R.H.

Letter Acuity Procedure

Bailey-Lovie visual acuity was assessed with chart 4 at 1 m ($n = 10$) or 2 m ($n = 9$) or closer when necessary ($n = 4$). LogMAR acuity was calculated using letter-by-letter scoring (0.02 logMAR per letter, after taking the test distance into account), with no letter substitutions allowed. The stopping rule was failure to correctly identify 3 of 5 letters on a row.

Grating Acuity Procedure

The Teller Acuity Cards were used with the standard, age-appropriate clinical procedure, at a testing distance of 55 cm.²³ The examiner observed the student's looking behavior and judged whether each grating was "seen" or "not seen," generally without using the peephole. The student's looking behavior was encouraged by suggesting that he/she points toward the grating using a "magic wand." The cards were presented under the descending method of limits, with the test ending when the observer determined that the student failed to see a grating. The examiner checked nearby card values to verify the measurement if necessary. To screen for possible luminance artifacts, the examiner asked the student whether he/she saw the "stripes" (i.e., the grating) or the "box" (i.e., any artifactual difference in reflectance between the grating and the gray card) near their acuity limit. Visual acuity was the cy/deg of the finest grating that the examiner judged the student could see by the "stripes" criterion.

Letter Contrast Sensitivity Procedure

We measured each student's contrast threshold using a calibrated Pelli-Robson chart. Testing distance was 1 m, except for two students with very poor acuity. Scoring was letter-by-letter, and each letter counted for 0.05 log units.²⁵ The test ended when a subject could not identify correctly at least two letters of a letter triad.

Ohio Contrast Cards Procedure

The testing methods for the Ohio Contrast cards closely paralleled the methods for the Teller Acuity Cards, with a test distance of 57 cm. Testing proceeded from high to low contrast using the descending method of limits, with extra cards presented near the contrast threshold limit if necessary. A student's contrast threshold was the lowest contrast value the examiner judged that the student was able to see.

Vision-related Quality-of-Life Assessment

The IVI_C questionnaire was administered orally by coauthor A. M.B. immediately after vision testing. The questions were read in a fixed order, and each of the alternatives was read out loud after each of the items.

Data Presentation and Analysis

Results comparing the vision tests are shown in \log_{10} units, with the range of available stimuli indicated as a dashed-line box on each figure. The contrast sensitivity results are expressed in (reciprocal) units of contrast threshold, and visual acuity results are expressed

in logMAR units. Thus, bigger numbers denote worse performance and appear to the right on the x axes and higher on the y axes on all the graphs. The paired data points from students who were tested in both eyes are joined by line segments. Three students failed to contribute complete data sets from one or both eyes: one Ohio State School for the Blind student was unable to read the letters of the Bailey-Lovie or the Pelli-Robson letter charts with either eye, but was able to perform the corresponding grating card tests with each eye; a second Ohio State School for the Blind student performed all four tests with his first eye, but could not read the letter charts with his second eye; one summer camp student did not provide Teller Acuity Card data with one eye. When data from one eye or one test were missing, the student's data could not contribute to the corresponding statistical analyses. Those data are shown on the primary data graphs (Figs. 3A, 3B, 4A, and 4B) at their correct positions for their successful tests, with their missing data plotted outside the range of available stimuli. Two students succeeded in identifying some letters on the charts, but did so at distances of 3 cm and 10 cm (students 1 and 2, respectively, on the graphs). Their data appear with small dots within their symbols, but their data are excluded from the statistical analyses of the letter charts. Their diagnoses are in the caption of Fig. 4. White symbols are for Ohio State School for the Blind students, and gray symbols are for the summer students.

We examined the possible associations between variables using mixed-effects analyses of variance, with "eyes" as a repeated measure within "students," and "school" as a fixed factor, along with whatever the covariate was for each analysis. For our Bland-Altman analyses, we normalized the x axis to be centered at $x = 0$, then tested the hypothesis that the y intercept was zero.

We used Rasch analysis (Winsteps version 3.69 software²⁶) with the Andrich rating scale model^{27,28} to score the IVI_C, collapsing the five-category to a three-category response scale¹⁵ and evaluating the performance of individual questions using fit statistics.^{29,30} The question about confidence in getting to school was eliminated from analyses because of an item infit mean square statistic outside published norms.^{26,30} We converted Rasch "person measures" to a 0- to 100-point scale for ease of interpretation.

RESULTS

Overall Results

The simplest indication of the utility of the Ohio Contrast Cards is that they were used successfully. Of 26 partially sighted students enrolled in the study, we obtained Ohio Contrast Card data from both eyes of 17 students and on one eye of 8 students (the other eye having no light perception). Malingering was detected in one additional student, and her data were eliminated from the data set.

Within students, vision in the two eyes was quite similar. This was revealed in preliminary analyses of variance under the general linear model, with "better/worse eye" (from the average of the grating and letter charts) crossed with "test" (letter chart vs. grating cards). For both visual acuity and contrast threshold, there was an effect of test but no effect of better versus worse eye ($F_{1,60} = 1.530$, $P = .221$, for acuity; $F_{1,60} = 1.368$, $P = .247$, for contrast threshold). The similarity of performance across eyes is not surprising because most students' blinding conditions were presumptively bilateral (Appendix A, available at <http://links.lww>).

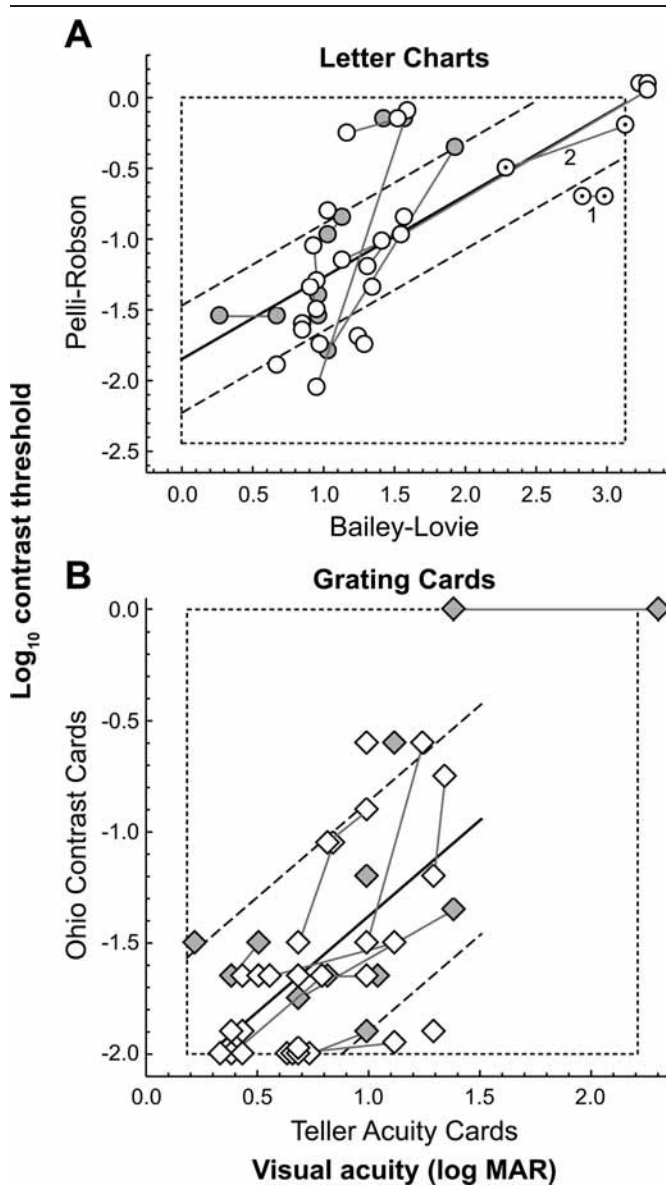


FIGURE 3. Comparison between visual acuity and contrast threshold performance. White symbols, Ohio State School for the Blind students; gray symbols, summer camp students; lines join students' fellow eyes; superimposed data points have been jittered in position by 0.05 or less for visibility on the graph. Dotted boxes: range of stimulus values available; symbols outside the boxes are incomplete data on students who could perform only one of the tests. Dots: stimuli viewed at 3 or 10 cm. Solid linear regression lines were fitted to the data by the mixed-effects analysis. (A) Letter charts; dashed lines, range of reproducibility for Pelli-Robson scores on low-vision patients from Dougherty et al.²⁵ (B) Grating cards; dashed lines, range of reproducibility of the Teller Acuity Cards on deaf-blind students.²³

com/OPX/A302). There was no difference in the overall level of visual performance between the Ohio State School for the Blind and summer students on a multivariate ANOVA after pooling data across the two eyes ($F_{4,18} = 1.510, P = .241$).

Clinically, it is often useful to compare a patient's contrast sensitivity to his/her visual acuity.³¹ The mixed-procedures analysis revealed strong associations between Bailey-Lovie logMAR acuity and Pelli-Robson contrast threshold (Fig. 3A: $F_{1,22.740} = 30.392,$

$P < .0001$) and between the Teller Acuity Card and Ohio Contrast Card results (Fig. 3B: $F_{1,30.606} = 8.613, P = .006$), after eliminating nonsignificant effects for school.

Grating Tests Versus Letter Tests

Figures 4A and 4B compare the performance on the grating tests to the corresponding letter tests. Most data fell below the solid equality lines (slope = 1), indicating that the grating tests revealed better performance than the letter tests. Teller Acuity Card logMAR performance depended on the Bailey-Lovie logMAR value ($F_{1,22.964} = 40.294, P < .0001$), after eliminating a nonsignificant effect of school. Contrast threshold measured using the Ohio Contrast Cards was associated with Pelli-Robson contrast threshold (Fig. 4A: $F_{1,32.913} = 33.078, P < .0001$) and also with school ($F_{1,32.935} = 5.881, P = .021$). The contrast threshold data generally fell below the lower dashed line (Fig. 4B), indicating that performance on the grating tests was often better than the best prediction from the limit of reproducibility on Pelli-Robson chart.²⁵

The results from Figs. 4A and 4B are shown as Bland-Altman³³ plots in Figs. 5A and 5B, which show the signed differences between the logarithms of the letter and grating scores as a function of their means. The Bland-Altman acuity difference did not depend significantly on the Bland-Altman mean acuity score ($F_{1,27.797} = 3.262, P = .082$), but there was a statistically significant effect of school ($F_{1,32.212} = 7.059, \log\text{MAR}, P = .012$). After averaging across eyes (for the students who were tested in both eyes), post hoc *t* tests revealed a significant residual for Ohio State School for the Blind students (mean, 0.373 [SD, 0.237]; $t_{12} = 5.447; P > .0001$), but no significant residual for the summer students (mean, 0.194 [SD, 0.300]; $t_7 = 1.72$; not statistically significant). For the contrast data, the Bland-Altman difference data did not depend significantly on the Bland-Altman average data ($F_{1,27.209} = 1.312, P = .262$). School was significant overall ($F_{1,27.726} = 4.944, P = .034$). After pooling across eyes, the average value for the Ohio State School for the Blind students was significantly above zero (mean, 0.458 [SD, 0.249]; $t_{12} = 6.367; P < .0001$), whereas the average for the summer camp students (mean, 0.159; $t_7 = 0.974$; not statistically significant) was not above zero. The results for both visual acuity and contrast sensitivity averages remained statistically significant after correction for two post hoc comparisons in each case.

Thus, Bland-Altman analysis confirms the impression from Fig. 4 that performance on the grating tests was generally better than performance on the letter charts for the Ohio State School for the Blind students, whereas the summer students did about the same on the letter charts and grating cards.

Modeling the Pelli-Robson Contrast Sensitivity Results

The Pelli-Robson chart was designed to test contrast sensitivity near the peak of the contrast sensitivity function, that is, at 3 m for the normal observer. In their original article, Pelli et al.⁴ suggested adjusting the test distance for low-vision patients, and a 1-m test distance is commonly used when the patient has reduced visual acuity. We tested at 1 m for all but two students (students 1 and 2). However, even the 1-m standard may be inappropriate for some low-vision patients. Contrast sensitivity measured using the Pelli-Robson chart could fall short of both the optimum contrast sensitivity and the contrast sensitivity measured using square-wave gratings, for this reason alone.

We dealt with this problem by performing a post hoc analysis comparing the empirical Pelli-Robson contrast sensitivity to the

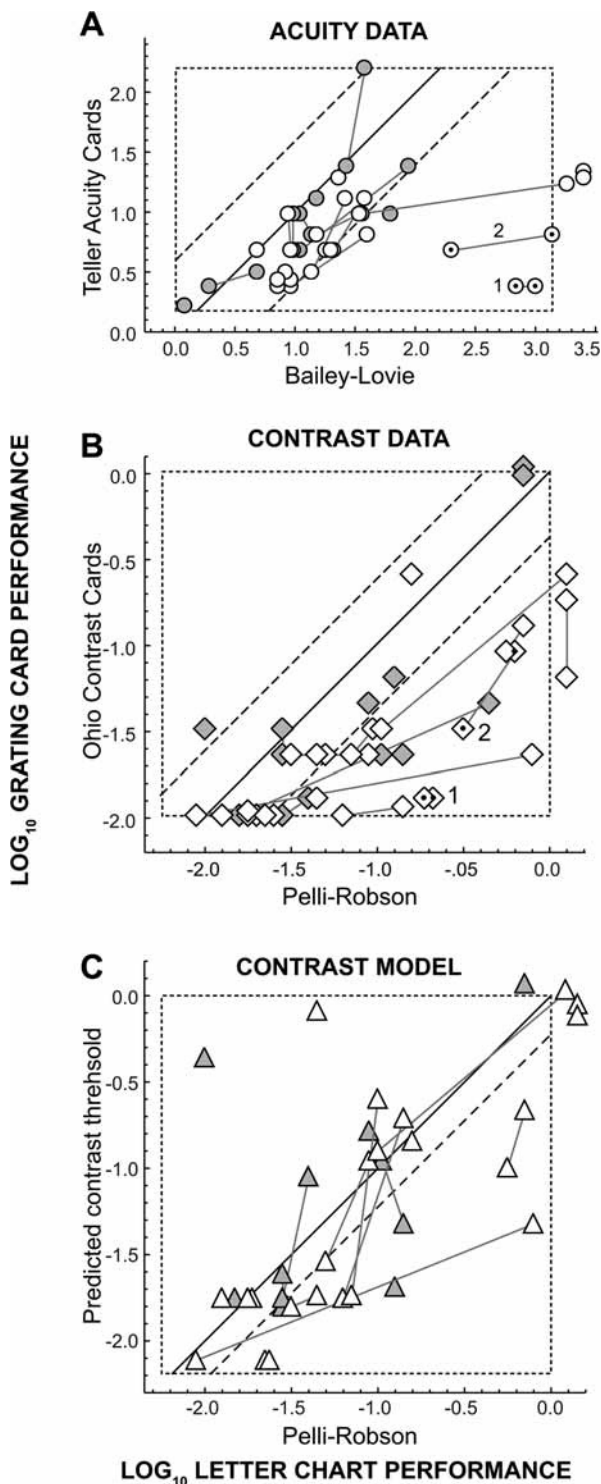


FIGURE 4. Performance on grating card tests compared with performance on letter charts. Graphic conventions as in Fig. 3. (A) Visual acuity. (B) Contrast threshold. Solid lines, equality predictions; dashed lines, limits of reproducibility from the Pelli-Robson chart³² and the Teller Acuity Cards,²³ as in Fig. 3. (C) The estimated grating contrast sensitivity from the model described in the text as a function of the Pelli-Robson contrast sensitivity. Dashed line in C: prediction from the requirement of identifying the letters rather than simply detecting them. Diagnoses of numbered students: student 1, cortical vision impairment; student 2, optic atrophy. See text for further details.

predicted level of the contrast sensitivity function at the spatial frequency of the Pelli-Robson letters at 1 m. We modeled the square-wave contrast sensitivity function using the square-wave template in Fig. 1A,⁵ which was based on the standard model of contrast detection.^{20,21} We assumed linear pooling of contrast within spatial frequency-tuned channels, and we used the parameters for channel spacing (0.5 octave), channel bandwidth (1.4 octaves) and channel pooling Minkowski exponent ($\beta = 4$) from Table 2 of Watson and Ahumada.²¹ The high constant contrast sensitivity at low spatial frequencies occurs because the contrast of the many harmonic components of the Fourier spectrum of the square wave decreases with increasing spatial frequency, but this decrease is matched by the increasing density of the harmonics along a log spatial-frequency axis.

We translated the contrast sensitivity function template relative to log spatial frequency and log contrast sensitivity axes to match the student's Teller Acuity Card and Ohio Contrast Card threshold data. This strategy requires the reasonable assumption that the shape of the spatial contrast sensitivity function for square waves, like the contrast sensitivity function shape for sine waves, is the same for low-vision students as for normally sighted individuals (Fig. 1C).⁹ We then used that template to estimate the spatial frequency and contrast sensitivity of the peak of the square-wave contrast sensitivity function for each student and also his/her contrast sensitivity at the peak of the spatial frequency band used to identify the Pelli-Robson letters. We estimated this channel frequency to be 1.466 cy/deg, using the formula from Majaj et al,³⁴ which has been replicated by others³⁵ and was also shown to apply equally well to the visual periphery of normally sighted eyes⁹ (see Fig. 4A of Chung and Legge⁹) and to the central vision of amblyopic eyes.³⁶ For comparison, the spatial frequency suggested by the three legs of the Sloan E (2.5 cy/letter) was 0.889 cy/deg at 1 m. We discuss the implications of this choice of spatial frequency below. The Pelli-Robson scores for students 1 and 2, who were tested at distances much closer than 1 m, were omitted from the corresponding graphs and analyses.

Figure 6A shows the template fitted to a typical student's Teller Acuity Card (black dot) and Ohio Contrast Card (red dot) data. The contrast sensitivity function allowed us to estimate the spatial frequency and the level of maximum sensitivity (blue diamond) and the level of contrast sensitivity at the spatial frequency of the Pelli-Robson letters (yellow square). Quantity *a* is the amount by which the Ohio Contrast Cards underestimate contrast sensitivity relative to the maximum contrast sensitivity of which the student is capable, quantity *b* is the amount by which the Pelli-Robson chart is predicted to underestimate contrast sensitivity relative to the maximum based on the visibility of the letters alone, quantity *c* is the amount by which student Pelli-Robson performance differs from its predicted value, and the sum of quantities *b* + *c* is the amount that empirical Pelli-Robson performance falls below the maximum. Figs. 6B and 6C show some examples of data and their fitted contrast sensitivity functions.

Best Test Distance

Although Pelli and his colleagues⁴ suggested a testing distance of 3 m, the testing distance in a low-vision setting is 1 m by convention. If the testing distance is much too long, the fundamental spatial frequency of the Pelli-Robson letters will be well onto the falling limb of the contrast sensitivity function (Fig. 6), and the patient's full visual ability to detect contrast will not be measured. The spatial frequency at the maximum of the model contrast sensitivity

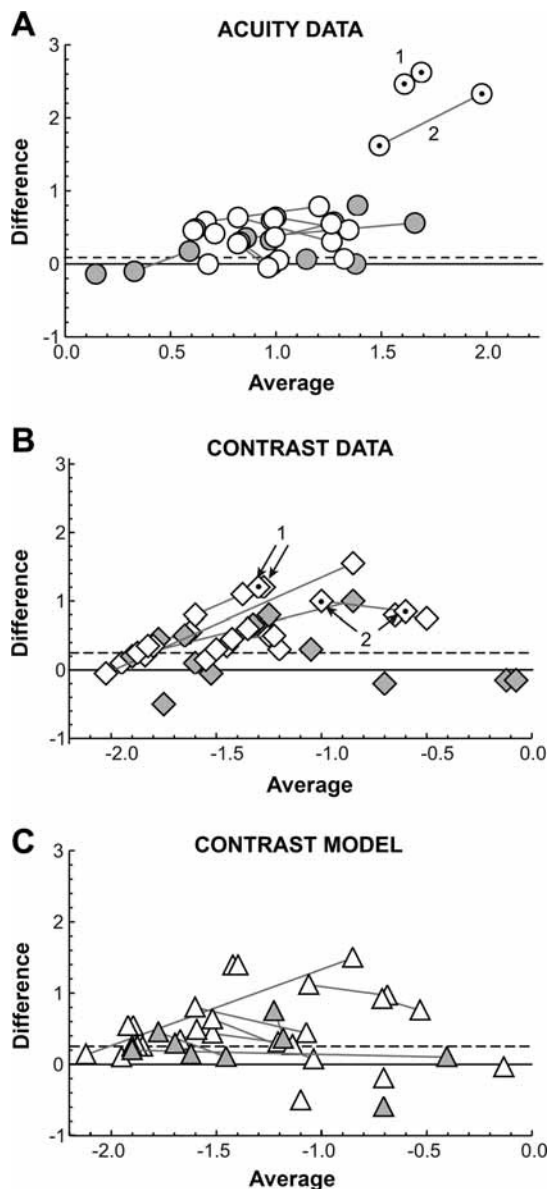


FIGURE 5. Results from Fig. 4 shown as Bland-Altman plots: the difference between the logarithms of letter performance and grating performance is shown as a function of their average. Symbol conventions as in Fig. 3. Data would fall on the zero lines if the two measures in each chart were numerically equal. Dashed lines: predictions from the requirement of identifying the letters, as explained in the text. (A) logMAR values from the Bailey-Lovie Chart and the Teller Acuity Cards. (B) Pelli-Robson chart and the Ohio Contrast Cards. (C) Pelli-Robson chart and the predicted Pelli-Robson contrast sensitivity.

function model allows us to estimate the best testing distance for each eye in this study (shown in Fig. 7A). Fifty-eight percent of students' eyes needed to be tested at 0.5 m or closer, and 16% of students' eyes needed to be tested at 0.25 m or closer. When the Pelli-Robson chart is used clinically, the examiner often has the patient's Bailey-Lovie logMAR acuity (VA) in hand, so Fig. 7B compares the estimated best test distance to the logMAR data of each eye. This association was statistically significant ($F_{1,34} = 42.170, P < .0001$) after eliminating students 1 and 2 and the data from eyes for which logMAR data were not

available. The results in Fig. 7B suggest a mnemonic rule of thumb: the testing distance in meters should be approximately $(1.5 - VA)$ meters (solid line). Testing distances farther than $(2 - VA)$ meters are too far away, and distances closer than $(1 - VA)$ meters are probably too close (upper and lower dashed lines, respectively).

Predicted Pelli-Robson Performance

Fig. 4C shows the predicted square-wave contrast sensitivity at the Pelli-Robson spatial frequency for each student as a function of his/her observed Pelli-Robson score. These two quantities were reliably associated ($F_{1,23.984} = 18.143, P < .0001$ on a mixed-effects analysis), but there was no significant effect of school ($F_{1,23.760} = 2.966, P = .098$). A mixed-effects analysis showed that the Bland-Altman difference scores (Fig. 5C) did not depend on the Bland-Altman averages ($F_{1,32.390} = 0.011$, not statistically significant) or school ($F_{1,28.933} = 3.337, P = .078$, not statistically significant). After pooling across eyes, the Bland-Altman difference scores were not different from zero (mean, -0.018 ; $t_{20} = -0.194$, not statistically significant). Thus, the model fit the data quite well, suggesting that students identified the letters at about the same level of contrast as they required to detect them.

Estimating Student Visual Capabilities

It is natural to wonder how well the Pelli-Robson chart and Ohio Contrast Cards estimated the best contrast sensitivity of which a student was capable, when tested at the best distance. One advantage of the Ohio Contrast Cards is that their grating spatial frequency (0.15 c/deg) was almost always below the maximum of the contrast sensitivity function (the red dots were mostly to the left of the blue diamonds in Fig. 6), so the maximum possible error is set by quantity e in Fig. 6A, that is, the separation ($-0.189 \log_{10}$ units, or a factor of approximately 0.65) between the peak of the contrast sensitivity function and the constant contrast sensitivity level at low spatial frequencies. In fact, 67% of the values of a were less than $0.15 \log_{10}$ units (white bars in Fig. 7C). By comparison, the contrast sensitivity at the Pelli-Robson letter frequency (1.47 cy/deg) could be much lower than the maximum of the contrast sensitivity function (quantity b). Only 29% of the estimated values of b were less than $0.15 \log_{10}$ unit, the median value of b was $0.36 \log_{10}$ unit, and for two eyes, b was more than $1 \log_{10}$ unit (gray bars in Fig. 7C). Thus, the letters were not optimally visible to the students. As discussed previously, the empirical Pelli-Robson contrast sensitivity (upright green triangle in Fig. 6A) was not significantly different from the estimated square-wave contrast sensitivity at the Pelli Robson frequency (Figs. 3C, 4C), so the average value of quantity c was not significantly different from zero (mean, 0.091 [SD, 0.447]; $t_{30} = 0.938$; not statistically significant). The median value of $(b + c)$ (black bars in Fig. 7C) was $0.507 \log_{10}$ unit (mean, 0.516 [SD, 0.363]). In short, performance in identifying the Pelli-Robson letters was far short of the best students could have achieved.

Identifying Letters

With the corrected grating contrast sensitivity data from our theoretical analysis in hand, we are in a position to determine whether the same individuals showed reduced letter chart performance on both the acuity and the contrast measures. Figure 8 shows the amount by which each student's Pelli-Robson score fell short of the prediction based on his/her contrast sensitivity function (quantity c in Fig. 6A), as a function of the amount by which his/her Bailey-Lovie score fell short of his/her Teller Acuity Card

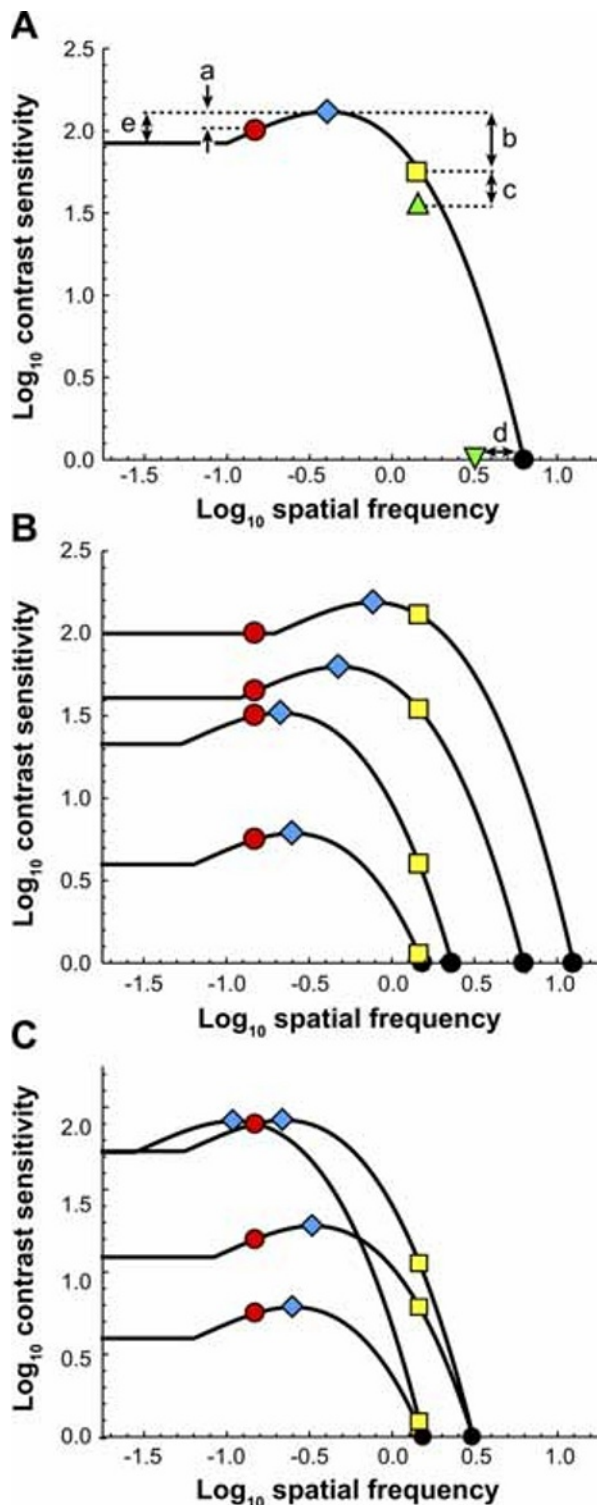


FIGURE 6. Predicted contrast sensitivity functions (CSFs) for square waves fitted to the grating card data. (A) Diagram of the model, for one eye. Circles, measured values: red circle, Ohio Contrast Card contrast sensitivity; black circle, Teller Acuity Card visual acuity; blue diamond: the maximum of the fitted CSF; yellow square: predicted sensory contrast sensitivity for the Pelli-Robson chart; green upright triangle, measured Pelli-Robson contrast sensitivity; green inverted triangle, measured Bailey-Lovie visual acuity. Quantities a to e: see text for definitions. (B and C) Examples of student CSFs.

score (quantity d in Fig. 6A). After eliminating the nonsignificant effect of school, the mixed-effects analysis of variance revealed that quantities c and d were highly associated with each other ($F_{1,27,012} = 14.084$, $P < .0001$). A linear regression line fit the data well: $c = -0.140 + 0.827 * d$ (bold line in Fig. 8). This suggests that students varied in their skill in identifying letters and that this variation had a similar impact on their overall visual performance on both eye charts.

Our Modeling Assumptions

Of course, the contrast sensitivity function on which these analyses are based is the model described in the introduction, and the spatial frequency band that students used to identify the Pelli-Robson letters is the value from Majaj et al,³⁴ Chung and Legge,⁹ and Pelli et al.³⁶ We tried various other templates, including ones with higher and lower horizontal sections at low spatial frequencies and more or fewer broadly or narrowly tuned channels, and found little qualitative difference from the predictions we report here. We also investigated the impact of assuming that the spatial frequency band used to identify the Pelli-Robson letters was 0.889 cy/deg (2.5 cy/letter, as for the Sloan E²²). For the lower letter spatial frequency, quantity b was smaller than we estimate here (but still statistically highly significantly different from zero), but c was larger (and statistically significant for students in both schools), but the sum $b + c$ (black bars in Fig. 7C) was not affected. Further research will be required to evaluate these assumptions empirically.

Vision-related Quality of Life

The main reason for measuring a visually disabled patient's contrast sensitivity is to understand the likely impact of the patient's low vision on his/her vision-related quality of life. Therefore, for students who provided data from both eyes, we chose the eye with the better logMAR acuity on the Bailey-Lovie Chart for comparison to the IVI_C scores because we expected that the better eyes would be the limiting visual factor in our students' lives. For students who used only one eye, the tested eye's vision data were used. Data from students who did not provide all four measures on at least one eye were excluded from the analysis.

Because the four vision tests were highly correlated with one another (Figs. 3, 4), we performed a stepwise linear regression to find the vision test(s) that accounted for statistically significant amounts of the variance in the IVI_C scores, while controlling for the significant correlations among the vision tests, with an additional factor for school. Only the Ohio Contrast Card data were significantly related to students' scores on the IVI_C test (partial correlation coefficient = -0.565 , $t = -3.134$, $P = .005$; Fig. 9). The other three vision tests showed partial correlations between -0.061 and $+0.136$, $P > .548$, and the partial correlation for school was -0.330 , $P = .133$. We obtained similar results when we eliminated the rightmost data point in Fig. 9 as a possible outlier: only the Ohio Contrast Card data predicted the IVI_C scores (partial correlation coefficient = -0.565 , $t = -3.134$, $P = .005$; the other three tests having partial correlations between -0.011 and 0.077 , $P > .650$, and there was still no effect of school). When we repeated the analysis while excluding the Ohio Contrast Card data, the Pelli-Robson data were strongly related to IVI_C scores (partial correlation coefficient = -0.563 , $t = -3.742$, $P = .001$), with a significant effect of school (partial correlation coefficient = -0.486 , $t = -3.332$, $P = .001$), with Ohio State School for the Blind students having a more satisfactory vision-related quality of life. These results suggest that the

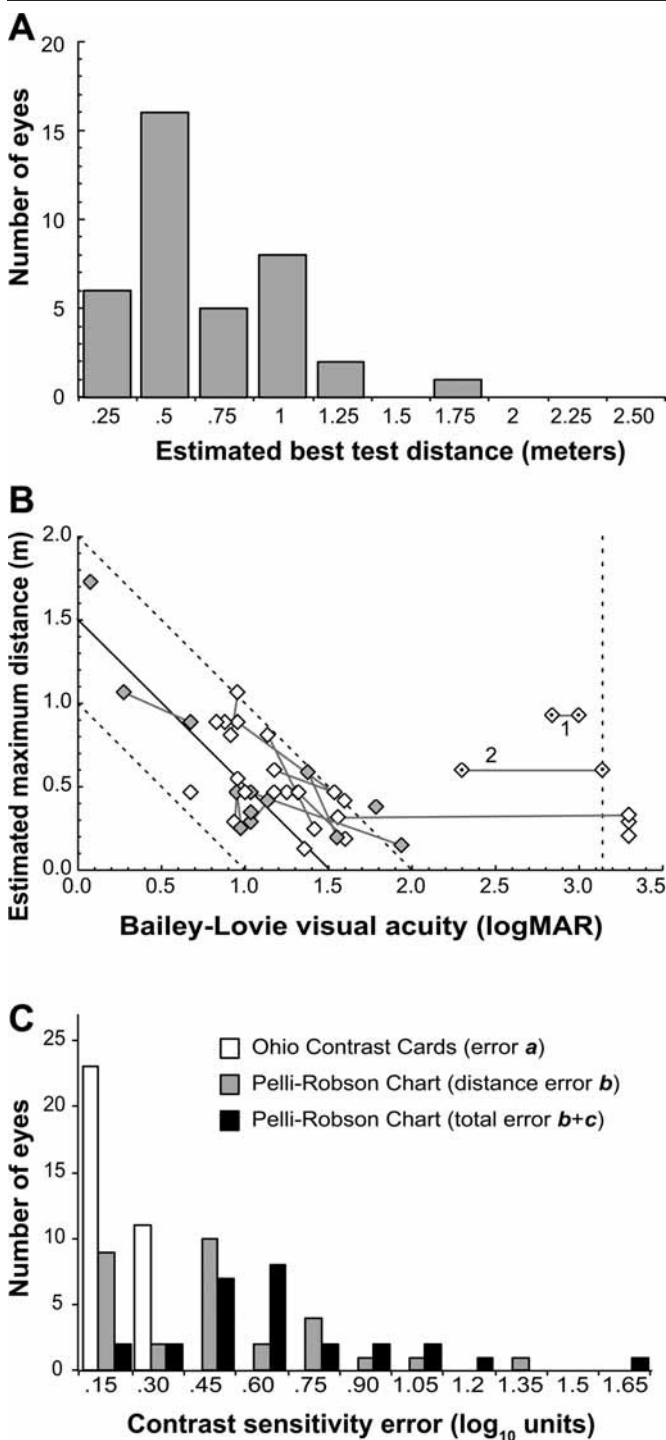


FIGURE 7. Estimated best test distance from the model. (A) Histogram of distribution for this sample of students. (B) Best test distance as a function of students' grating acuity. Fellow eyes joined by lines. Diagonal solid line: rule of thumb proposed in the text. (C) Histogram of the contrast sensitivity errors for three estimates of contrast sensitivity; see text for further details.

Pelli-Robson chart can also provide valuable information. Together, these analyses point to sensory visual contrast sensitivity as a potent predictor of vision-related quality of life, as other investigators have found.²

DISCUSSION

In this project, we compared the results of four vision tests, including the new Ohio Contrast Card test. The four test results were generally correlated with one another. However, as is the common experience of clinicians who use both tests, performance on the Teller Acuity Cards was generally better, and often substantially better, than the performance on the Bailey-Lovie letter chart. This result is in good agreement with recent work of Bittner et al.³⁷

Of the four tests we examined, only better contrast sensitivity on the Ohio Contrast Cards was independently associated with better vision-related quality of life as indicated by the IVI_C questionnaire. We suspect that this strong association occurred because these students' vision-related quality of life is mostly determined by their limited ability to perform simple, everyday tasks for which large stimuli are the most important. For example, orientation and mobility require the ability to see the terrain underfoot, stairs, doorways, and large obstacles, and social interactions benefit from the ability to see people's faces and to judge people's emotions from their posture. All these aspects of these students' lives depend on the visibility of stimuli that become hard to see when they are too low in contrast, not when they are too small, and none of them depend on students' ability to recognize and identify letters or other optotypes.

Performance for Gratings Versus Letters

Our modeling exercise showed that student ability to see and identify optotypes was compromised compared with what is expected in a normally sighted person. In the case of the Pelli-Robson chart, this is probably mostly a sensory deficit, because the observed Pelli-Robson performance was similar to the prediction based on the estimated contrast sensitivity function. By comparison, student performance on the Bailey-Lovie chart was generally below the high spatial frequency cutoff predicted by their Teller Acuity Card performance, suggesting that there are additional limitations on letter acuity.

We consider two additional limitations, which probably apply to both contrast sensitivity and acuity. First, even for normally sighted observers, a higher level of contrast is generally required to identify stimuli, rather than to simply detect them.^{38,39} The dashed fiducial lines in Figs. 4C, 5B, and 5C are based on the estimate from Pelli et al.³⁸ that 0.230 \log_{10} units higher contrast is required for identifying letters than for detecting them. The fiducial lines agree with the residual results reasonably well on average, even though the Bland-Altman average data are not different from zero, because the residual variance is quite large. To obtain a prediction for visual acuity, we translated the contrast sensitivity function template downward by 0.230 \log_{10} units to predict the acuity cutoff for identifying letters. For a typical student with average Ohio Contrast Card and Teller Acuity Card performance, the estimated Bailey-Lovie logMAR acuity was 0.104 \log_{10} units below the Teller Acuity Card cutoff (dashed line in Fig. 5A). Quantity *d* was statistically significantly larger than 0.104 log units ($t_{31} = 4.227, P > .0001$). Thus, the additional contrast required for letter identification is consistent with the Pelli-Robson data, but does explain the poor Bailey-Lovie Chart data compared with the Teller Acuity Card acuity data.

Second, there may be additional difficulties posed by the task of identifying the optotypes on an eye chart. For example, if a student has a scotoma that conceals part of an optotype such as a letter,

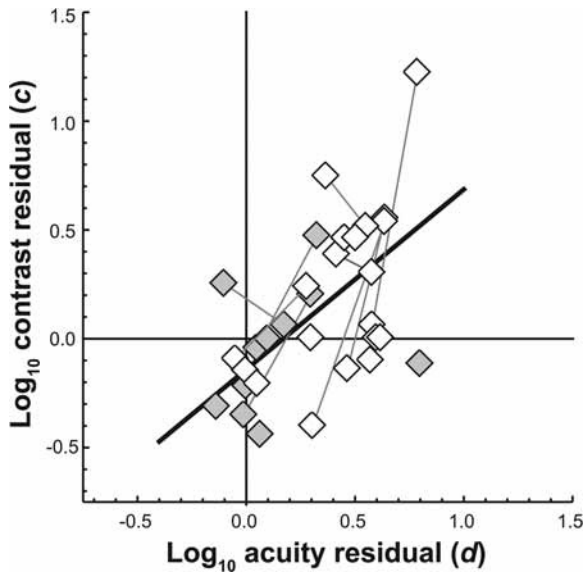


FIGURE 8. Residual differences between predicted and observed performance. Fellow eyes joined by lines. Bold regression line was fitted to the data after averaging the two eyes' data within students. See text for further details.

he/she must scan the various parts of the letter to identify it. This makes letter identification more a question of educated inference than of actual recognition or reading. A scotoma is likely a more important factor for optotypes near the acuity limit than it is for the larger letters of the Pelli-Robson chart. By comparison, a grating is simply detected in the card tests we used here, not recognized or identified. Furthermore, the information for grating detection is distributed throughout the stimulus, and the student may be able to find it on the left or right of the card, even if the grating as a whole is only partly seen (see Bittner et al.³⁷ for a similar discussion). Many stimuli that a partially sighted student sees cover a large part of the visual field (e.g., a wall), even when the specific stimulus (e.g., the edge of a doorway) is localized. For this reason, measuring the visibility of a large contrast or acuity grating may be a better way of determining how well a student with compromised visual capabilities can function in everyday life. This observation is in good agreement with the strong association between the Ohio Contrast Card data and the IVI_C results.

Several individual students had such great difficulty reading the letters that the explanations offered previously seem inadequate. Students 1 and 2 had severely compromised performance on the Pelli-Robson chart despite being tested at only a few centimeters' distance, and a third student was unable to identify the letters on either letter chart (data plotted outside the boxes in Figs. 3 and 4). It is beyond the scope of this article to determine what specifically caused these outlying and excluded students' difficulty in identifying letters in the presence of often much better performance on the card tests. However, we note that all were intellectually able, keeping up with their curriculum using Braille and other accommodations. The vision-related quality-of-life scores for students 1 and 2 are indicated in Fig. 9, which shows that these students were not obviously more disabled than the other partially sighted students in this study.

We particularly draw the reader's attention to student 1, who had cortical visual impairment. He was an outlier on most graphs because his grating performance was so much better than his

letter performance. His better-eye performance on the letter charts revealed 2.84 logMAR (20/1400) visual acuity and 0.70 log₁₀ contrast sensitivity, whereas his performance on the grating cards revealed 0.397 logMAR (20/50) acuity and 1.9 log₁₀ contrast sensitivity. We suspect that student 1 might use dorsal-stream-based strategies⁴⁰ to interact with the physical world, perhaps mediated by a nonstriate pathway to the sensory-motor areas in the parietal cortex, which may have been spared by his injury. We note that he enjoys remarkably good mobility without a cane and succeeds in many other motor skills required in everyday life, despite his severe cortical vision impairment. The fact that the card tests used looking and pointing rather than recognizing or reading as the indicator task is consistent with this view.

The Ohio Contrast Cards

This project was designed to determine whether the Ohio Contrast Cards showed promise as a useful test for use with low-vision patients who cannot recognize and identify letters or other optotypes and for whom the spatial frequency maximum of the contrast sensitivity function is unknown. We recognize that this is only the first step in the development of this new test and that dedicated research on the reproducibility of the measurements will be required before it can be used with confidence in the clinic. Furthermore, work with patients in other settings, for example, elderly patients or patients with multiple disabilities, will be needed before we can confidently recommend the Ohio Contrast Cards for all types of clinical practice where visually impaired patients are seen.

The Ohio Contrast Cards were convenient to use in tandem with the Teller Acuity Cards. The typical Ohio State School for the Blind student showed approximately 0.458 log₁₀ units better performance on the Ohio Contrast Cards than on the Pelli-Robson chart

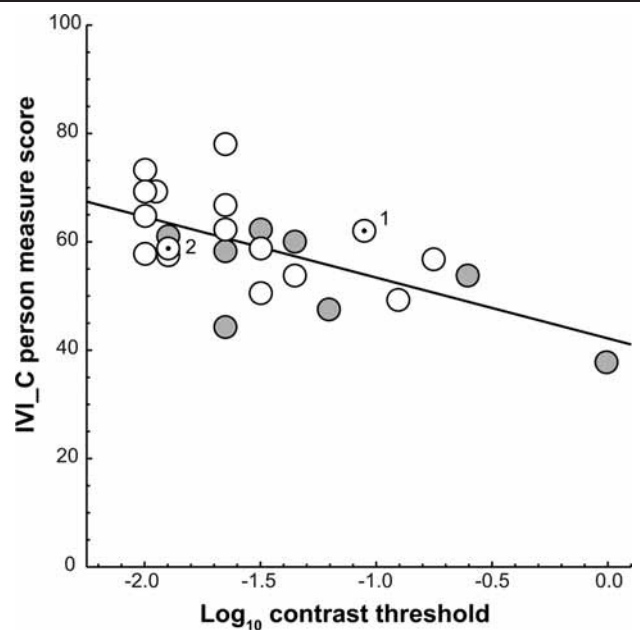


FIGURE 9. The statistically significant association between the Ohio Contrast Card test results and the Impact of Vision Impairment on Children vision-related quality-of-life questionnaire results. White symbols: Ohio State School for the Blind; gray symbols: Ohio State School for the Blind summer camp. Line: linear regression.

or approximately three groups of three letters on the Pelli-Robson chart. This difference is statistically significantly different and would probably be clinically significantly different as well. Similarly, the Teller Acuity Cards produced visual acuity values that are approximately 0.346 logMAR better than the Bailey-Lovie Chart, a difference that is statistically significant and at approximately 3.5 lines on the Bailey-Lovie Chart is also clinically significant. The Ohio Contrast Card contrast sensitivity was the only one

of the four scores measured here that correlated statistically significantly with students' scores on the IVI_C vision-related quality-of-life questionnaire. This suggested that the combination of a very low spatial frequency grating stimulus, a looking and pointing indicator task, and contrast sensitivity measurement shows promise for the clinical objective of advising the patient and his/her family and caregivers about the success the patient is likely to enjoy in the tasks of everyday life.

ARTICLE INFORMATION

Supplemental Digital Content:

Appendix A, a table that lists the student participants in this study, is available at <http://links.lww.com/OPX/A302>.

Appendix B, which lists the text of the IVI_C questionnaire, is available at <http://links.lww.com/OPX/A303>.

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Conflict of Interest Disclosure: None of the authors have reported a conflict of interest. The Ohio Contrast Cards are available for purchase, but the authors have no financial interest in any proceeds derived from the sale of the cards.

Author Contributions and Acknowledgments:

Conceptualization: GRH, AMB; Data Curation: GRH; Investigation, Methodology, Project Administration: GRH and AMB; Writing—Review and Editing: GRH, BED, AMB; Formal Analysis, Funding Acquisition, Resources, Supervision, and Writing—Original Draft: AMB.

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