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Measuring Resolution in the Contrast Domain: The Small Letter Contrast Test (Reprint)

By

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Recent evidence suggests that small letter contrast sensitivity (CS) is more sensitive than visual acuity (VA) to defocus, luminance, binocular enhancement, and visual differences among pilot trainees. It would be valuable to make this test available for general use. We developed a hard copy (letter chart) version called the Small Letter Contrast Test (SLCT) and evaluated its sensitivity and reliability in comparison to standard vision tests. The SLCT has 14 lines of letters with 10 letters per line. The letters are of constant size (20/25 or 4/5 at 4 m), but vary in contrast by line in 0.1 log steps (0.01 log units per letter). Normal room illumination is used. The SLCT was evaluated in 16 subjects under various conditions (spherical and astigmatic blur, low luminance, 2 eyes vs. 1 eye) to determine test sensitivity and reliability, and in patients with clinical conditions. Scores were compared to those obtained with standard tests of VA (Bailey-Lovie) and CS (Pelli-Robson). SLCT scores were similar to previous measures, and retest reliability was one line. The SLCT was more sensitive than VA to spherical and astigmatic blur, low luminance, and vision with two eyes vs. one eye. Greater sensitivity of the SLCT endured despite correction for variability. The SLCT was

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more sensitive than standard tests to visual loss from early cataract, keratoconus, corneal infiltrates, edema, and amblyopia. The SLCT is a sensitive, adjunctive test, which complements existing measures of VA. It can reveal subtle visual deficits that may be undetected by standard clinical techniques. The SLCT should prove useful for monitoring vision in refractive surgery, corneal and macular edema, optic neuritis, and for selection and evaluation of candidates for occupations requiring unique visual abilities like aviation.

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Measuring Resolution in the Contrast Domain: The Small Letter Contrast Test

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ABSTRACT

Background. **Recent evidence suggests that small letter contrast sensitivity (CS) is more sensitive than visual acuity (VA) to defocus, luminance, binocular enhancement, and visual differences among pilot trainees. It would be valuable to make this test available for general use. We developed a hard copy (letter chart) version called the Small Letter Contrast Test (SLCT) and evaluated its sensitivity and reliability in comparison to standard vision tests.** ***Methods.*** **The SLCT has 14 lines of letters with 10 letters per line. The letters are of constant size (20/25 or 4/5 at 4 m), but vary in contrast by line in 0.1 log steps (0.01 log units per letter). Normal room illumination is used. The SLCT was evaluated in 16 subjects under various conditions (spherical and astigmatic blur, low luminance, 2 eyes vs. 1 eye) to determine test sensitivity and reliability, and in patients with clinical conditions. Scores were compared to those obtained with standard tests of VA (Bailey-Lovie) and CS (Pelli-Robson).** ***Results.*** **SLCT scores were similar to previous measures, and retest reliability was one line. The SLCT was more sensitive than VA to spherical and astigmatic blur, low luminance, and vision with two eyes vs. one eye. Greater sensitivity of the SLCT endured despite correction for variability. The SLCT was more sensitive than standard tests to visual loss from early cataract, keratoconus, corneal infiltrates, edema, and amblyopia.** ***Conclusions.*** **The SLCT is a sensitive, adjunctive test, which complements existing measures of VA. It can reveal subtle visual deficits that may be undetected by standard clinical techniques. The SLCT should prove useful for monitoring vision in refractive surgery, corneal and macular edema, optic neuritis, and for selection and evaluation of candidates for occupations requiring unique visual abilities like aviation.**

Key Words: visual acuity, contrast sensitivity, vision testing, resolution, letter chart

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Optimal visual acuity (VA) is one goal of clinical vision care. Refraction of the eye, detection, diagnosis and treatment of ocular disease, and refractive surgery share the common goal of achieving best VA. The effectiveness of this approach is predicted on the fact that VA is a sensitive index of decreased vision. Blurring of vision, from optical defocus or other factors, typically causes a reduction in VA, and this reduction is generally proportional to the amount of blur. But blurring the retinal image also reduces the contrast of higher spatial frequencies. Because of the steep, descending slope of the spatial contrast sensitivity (CS) function near the acuity limit, a reduction in VA is associated with a relatively greater reduction in CS for higher spatial frequencies.

This principle is illustrated in Fig. 1, which shows that 1 D of defocus shifts the descending limb of the CS function downward and to the left. The shift leftward along the spatial frequency axis represents the reduction in VA. The shift downward along the contrast dimension demonstrates the greater reduction in CS for higher spatial frequencies.

The greater reduction in CS than VA suggests that small letter CS may provide a more sensitive index of blur. In previous studies, we used letters

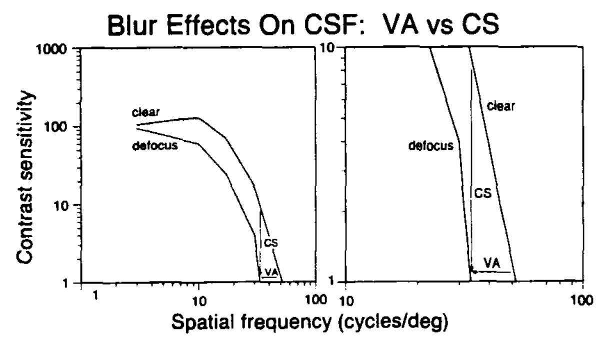

Figure 1. Effects of defocus on visual acuity (VA) and contrast sensitivity (CS). The left panel shows the CS function with and without defocus; the right panel shows an enlarged view of the descending limb. Defocus reduces the contrast of higher spatial frequencies shifting the CS function downward and to the left. Because of the steep descending slope, a reduction in VA is associated with a greater reduction in CS.

displayed on a computer monitor to show that small letter CS is more sensitive than VA to small amounts of blur,[1] subtle changes in the luminance of the stimulus,[2] vision with two eyes compared to one eye,[3] and for identifying visual differences among pilot trainees.[4–6] To make this test available for general use, we developed a hard copy (letter chart) version called the Small Letter Contrast Test (SLCT). This paper describes the design of the SLCT, its reliability, and its sensitivity for detecting differences from normal and changes within patients over time.

METHODS

The SLCT is generated from computer software (Adobe Photoshop version 2.0.1) on a Macintosh Quadra 800 computer. Helvetica bold font is used in gray scale mode, which affords 256 gray levels on white background. The SLCT is printed from a Kodak XL 7700 continuous tone digital printer, which uses a thermal dye sublimation process. Each SLCT is printed on 2 sheets of Kodak 8½ by 11 in Ektatherm print paper, trimmed and mounted to a single sheet of white gator board (45 by 30 cm; Fig. 2).

As illustrated in Fig. 2, the SLCT consists of 14 lines of letters with 10 letters per line. Like the Bailey-Lovie[7] and ETDRS[8] VA charts, the SLCT has a logarithmic progression from the top to the bottom. However, unlike VA, the letters are of constant size (approximately 20/25 or 4/5 at a 4-m viewing distance), but vary in contrast, by line, in 0.1 log unit steps. Credit is given for each letter read correctly[9] (0.01 log unit per letter). By using 10 letters per line and scoring by letter, the increment size is smaller than those available on other letter chart tests. A smaller increment size typically results in narrower confidence intervals, and thus greater sensitivity to change.[9] As noted earlier, small letters are used to: (1) test high spatial frequency channels like those used for VA, and (2) take advantage of the steep slope of the CS function for which small changes in VA are associated with large changes in CS.

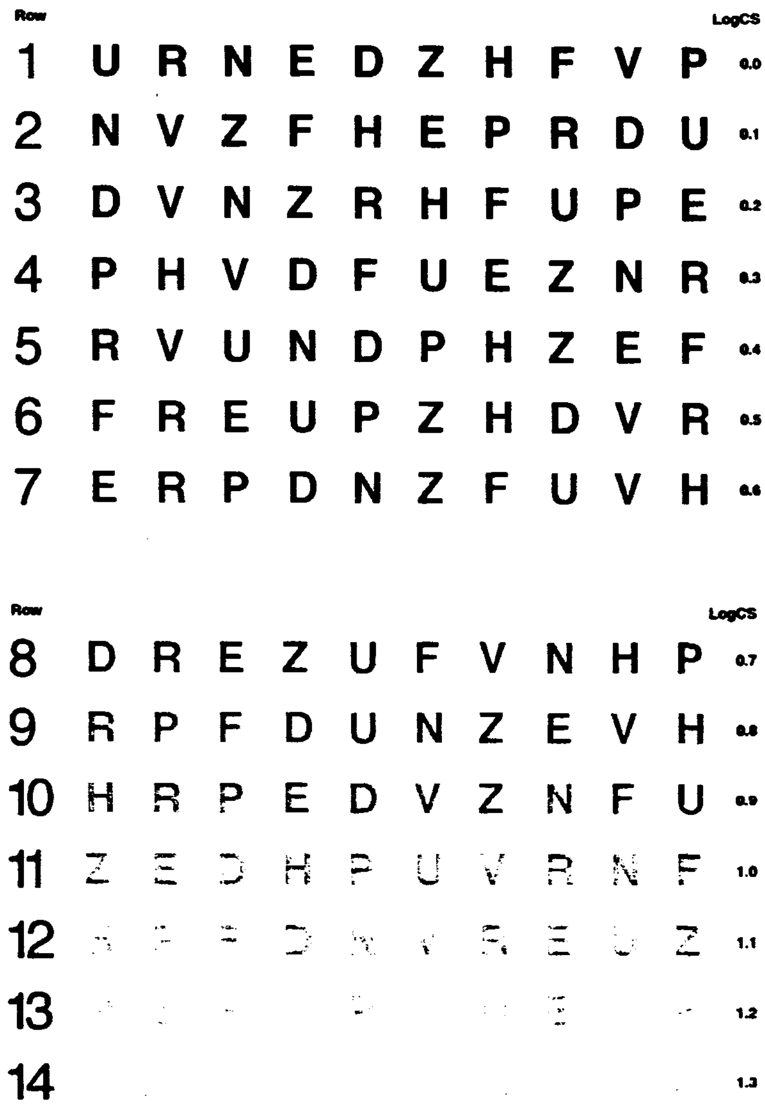

Figure 2. The Small Letter Contrast Test (SLCT). The SLCT has 14 lines with 10 letters per line. Contrast varies by line in 0.1 log steps. Normal room illumination is used (100 cd/m²).

Normal overhead room illumination (fluorescent or incandescent) is used on the SLCT. Fig. 3 (left) illustrates logCS scores computed from photometric measurement of the luminance of individual SLCT letters and their immediate background (Pritchard 1980 photometer). The measured logCS scores are in good agreement with intended values of 0.1 log unit per line (mean measured change in logCS per line = 0.10 ± 0.02 log units). Fig. 3 (right) also shows that the 0.1 log unit progression per line is valid for photopic room luminances ranging from 50 to 200 cd/m^2, although measured logCS values are slightly higher at 100 cd/m^2. SLCT scores from human observers are likely to vary in proportion to luminance over this photopic range.[2]

To evaluate the sensitivity and reliability of the SLCT, performance on this new test was compared to that obtained with standard tests of visual function. High and low contrast VA (Bailey-Lovie acuity charts),[5] large letter CS (Pelli-Robson chart),[10] and small letter CS (SLCT) were measured monocularly in 21 subjects with normal vision (ages 23 to 60 years) to establish mean values and confidence limits for normals. More extensive measurements were obtained from 16 of the 21 subjects (ages 23 to 35 years) to assess the sensitivity and reliability of each test to several conditions in which vision was compromised by small amounts. Subjects were tested under the following conditions in this order: (1) monocularly (right eye) with best optical correction, (2) low degree of spherical blur (+0.5 D) to simulate low myopia, which would preclude an officer candidate from being accepted for pilot training, (3) low degree of astigmatic blur (+1 D by 90), also a failure criterion for pilot training, (4) low level of photopic luminance (6 cd/m^2) to represent the luminance of a night vision goggle display, (5) binocularly to compare to monocular scores, and (6) again monocularly with best correction to assess retest reliability.

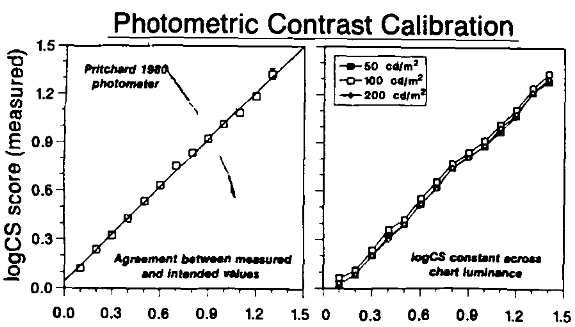

Figure 3. The left panel shows that logCS scores computed from photometric measurement of individual SLCT letters and background are in good agreement with intended values of 0.1 log unit per line. The right panel shows that this relation holds for 3 chart luminances (50, 100, and 200 cd/m^2) representing low, medium, and high room luminances (fluorescent lighting).

Each subject initially was refracted to best VA and then tested in a single session in a vision laboratory illuminated by overhead fluorescent lighting under rheostat control. The subject was seated comfortably and wore a trial frame such that the optical correction and different power lenses (+0.5 D sphere and +1 D by 90) and filter (low luminance condition) could be placed before the right eye. The viewing distance for high and low contrast VA and the SLCT was 4 m, whereas the Pelli-Robson chart was viewed at 1 m, as recommended by the manufacturer. Because each vision chart has two versions with different letter sequences, the letter sequence for each chart was alternated between trials to discourage learning effects. The luminance from the white background of the letter charts was 100 cd/m^2. In addition to these measurements from normal subjects, several observers with subtle visual loss from various conditions, such as cataract, keratoconus, corneal infiltrates, and amblyopia, also were tested but without induced blur or low luminance. In accord with the Declaration of Helsinki, informed consent was obtained from all subjects after protocol review by our institutional review committees.

RESULTS

Normative Data

A clinical vision test can be used to determine if vision *differs from normal* or *changes over time.* These are separate issues requiring distinct statistical comparisons. For example, a patient presents with a history of refractive surgery, and testing is conducted to determine if vision is normal on each test. Vision is considered below normal if the patient's scores fall below the 95% confidence limits for normal observers (i.e., 2 SDs below the mean; Table 1). But now, let's say we wish to determine if the same patient's vision changes over time. Then we need to obtain at least two measures from our patient, separated in time, to determine whether the difference in vision falls within the 95% confidence interval for differences between successive measures in normals. This interval, known as the coefficient of repeatability,[11, 12] is determined by computing the standard deviation of within-subject differ-

Table 1. Detecting differences from normal.[a]

Vision Test	Mean ±2 SD[b] (mean Snellen VA)	Below Normal
High contrast VA	−0.11 ± 0.12 (20/16)	20/21 or less
Low contrast VA	0.00 ± 0.14 (20/20)	20/28 or less
Pelli-Robson	1.88 ± 0.17	1.70 or less
SLCT	1.21 ± 0.18	1.02 or less

[a] Normal observers tested monocularly (N = 21, age 23 to 60 years).

[b] Decimal units are logMAR for VA and logCS for Pelli-Robson and SLCT.

TABLE 2. Detecting change over time.

Vision Test	Repeatability (log units)[a]	Significant Change (lines on chart)[b]
High contrast VA	0.06	4/5 line
Low contrast VA	0.07	4/5 line
Pelli-Robson	0.12	1 line
SLCT	0.11	1 line

[a] Coefficient of repeatability = 2.13 times SD of differences between two scores.

[b] For VA and SLCT one line = 0.1 log unit; for Pelli-Robson one line = 0.15 log units.

ences between scores on separate occasions, and multiplying by a factor of approximately two, depending on sample size.[a] Table 2 shows the coefficient of repeatability in log units for each test, and a significant change in vision in terms of lines of letters on each chart. A reduction of approximately one line of letters represents a significant decrease in vision on each test.

Test Sensitivity

Fig. 4 shows results from normal subjects (N = 16) tested under conditions of spherical blur, astigmatic blur, low luminance, and one eye vs. two eyes. The mean (±1 SE) reduction in vision is plotted in log units for each vision test. For each subject, the reduction in vision was computed by taking the difference between log scores under optimal conditions (best correction; monocular) and test conditions (spherical blur, astigmatic blur, low luminance, or binocular). Fig. 4 shows that 0.5 D of spherical blur reduced high and low contrast VA by only 0.1 log unit (one line of letters), but there was a larger, 0.3 log unit reduction on the SLCT—an average of three lines. As shown previously,[13] little change was observed with the Pelli-Robson chart, which uses large letters (low spatial frequencies) and is thus unaffected by small amounts of blur.

A similar, albeit larger, effect was observed with a small amount of astigmatic blur (+1 D by 90; Fig. 4). There was a 0.2 log unit (2-line) reduction in high and low contrast VA, but a greater, 0.55 log unit (5.5-line) reduction on the SLCT. Again, defocus had minimal impact on performance on the Pelli-Robson chart.

Although defocus simulates effects of refractive error, a decrease in stimulus luminance can reduce vision, perhaps in a manner similar to that imposed by opacities of the ocular media. Fig. 4 shows that reducing luminance within the photopic range (from 100 to 6 cd/m^2) produced a 0.1 log (1-line) decrease in high contrast VA, a 2-line decrease in low contrast VA, a 1.3-line decrease on the Pelli-Robson chart, but a larger 5-line decrease on the SLCT.

As in previous studies,[14, 15] vision with two eyes compared to one eye produced only a slight improvement in high and low contrast VA (two letters; Fig. 4), but a larger improvement in CS on the SLCT and Pelli-Robson tests (1.3 lines).[b]

Results presented thus far suggest that the SLCT is more sensitive than standard letter chart tests to small amounts of blur, modest changes in stimulus luminance, and binocular enhancement. However, a larger effect does not ensure increased test sensitivity if variability is also greater. To standardize scores with respect to variability, the difference between each score and the value under optimal conditions was divided by the standard deviation of the measurement. This transformation, which expresses all test scores in common units of standard deviations, allows for direct comparison between results of different tests. Fig. 5 shows test sensitivity standardized relative to variability between (left) and within subjects (right). Values at the left represent the difference between each score and the normal group mean under optimal conditions divided by the *group standard deviation*. Values plotted at the right were computed from the difference between each individual's test score and optimal score divided by the *within-subject standard deviation*. Despite these corrections for variability, both between- and within- subjects, the SLCT still proved to be at least 2 times more sensitive than standard vision tests under most conditions.

Application in Clinical Conditions

Fig. 6 shows results of letter chart testing in several clinical conditions characterized by subtle decreases in vision. For each patient, the reduction in vision is plotted as standard deviations below the mean for normal subjects (N = 21). In each condition, including early nuclear cataract, previously undiagnosed keratoconus, mild amblyopia, corneal infiltrates, and contact lens edema, the SLCT clearly is as sensitive, if not more sensitive, than standard vision tests for detecting subtle differences from normal.

[a] Because multiple measures were taken within a single session, it is possible that practice or fatigue influenced the results. However, paired t-tests revealed no significant difference between first and final measures of high contrast VA (t = 1.9, p > 0.07), SLCT (t = 1.9, p > 0.08), and Pelli-Robson scores (t = 0, p = 1.0), and only a slight improvement (<1 letter) on the second measure of low contrast VA (t = 2.2, p = 0.047). Moreover, when the coefficient of repeatability was computed from successive measurements separated by a longer period of time (3 weeks; N = 8 subjects), values were still one line of letters for high contrast VA (0.09 log units) and SLCT (0.10 log units), indicating that a longer interval between measures does not significantly increase variability.

[b] Because some subjects scored near the maximum when tested monocularly on the SLCT, they were retested at a greater viewing distance (4.8 m) to obtain binocular scores that represented the full extent of enhancement. This factor, and the larger step size on the Pelli-Robson chart (0.05 log units per letter), may have contributed to greater binocular enhancement on the Pelli-Robson chart.

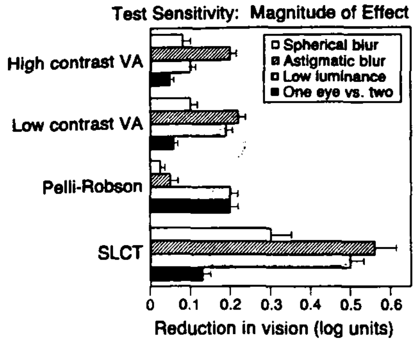

Figure 4. The mean (±1 SE; N = 16 subjects) reduction in vision in response to +0.5 D of spherical blur, +1 D by 90 astigmatic blur, a modest decrease in photopic luminance (from 100 to 6 cd/m^2), and vision with one eye vs. two eyes is plotted for each vision test. The reduction in vision was computed by taking the difference between log scores under optimal conditions (best correction; monocular) and test conditions (spherical blur, astigmatic blur, low luminance, or binocular).

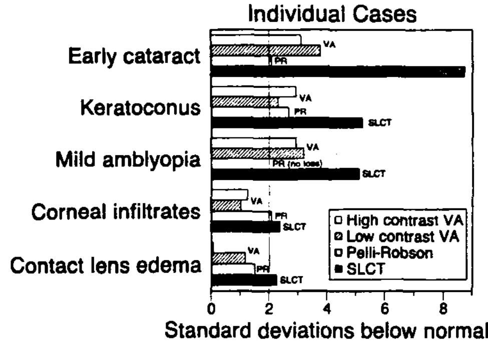

Figure 6. Letter chart testing in individual clinical cases characterized by subtle visual loss. For each condition (early nuclear cataract, previously undiagnosed keratoconus, mild amblyopia, corneal infiltrates, and contact lens edema), the reduction in vision is plotted as standard deviations from the mean for normal subjects (N = 21). The SLCT is clearly as sensitive if not more sensitive than standard tests for detecting subtle differences from normal.

Fig. 7 shows results from two patients, one with an early nuclear cataract in his right eye (left), and a second with mild amblyopia, also in the right eye (right). In each case, high contrast VA is shown at the top, and the difference between log scores of the better eye and the affected eye (LE-RE) is plotted for each test. In the patient with cataract, there was a two-line difference between eyes in high and low contrast VA, and a one-line difference on the Pelli-Robson chart, but the difference between eyes on the SLCT was much greater—five lines. Perhaps if this patient had been tested earlier in the course of the cataract, then the only significant finding may have been on the SLCT. In the patient with amblyopia, there was less than one-line difference between eyes in high contrast VA, and 1.2 lines with low contrast VA, but a four-line difference between the two eyes on the SLCT, underscoring the sensitivity of this test to subtle visual loss. The lack of any difference between eyes on the Pelli-Robson test suggests that the amblyopic deficit was limited to higher spatial frequencies.

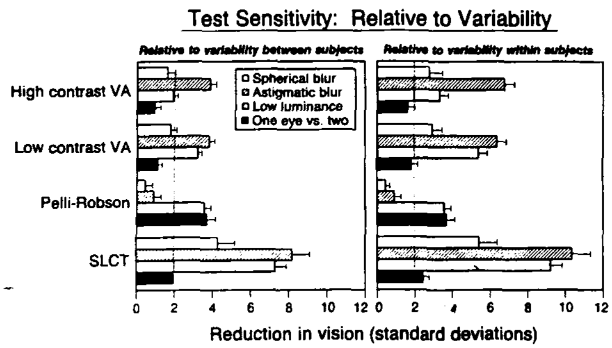

Figure 5. Mean (±1 SE; N = 16 subjects) sensitivity of each vision test is plotted as standard deviations. Data at the left were computed by taking the difference between each score and the mean under optimal conditions divided by the *group standard deviation*. Data at the right represent the difference between each individual's score and the score under optimal conditions divided by the *within subject standard deviation*. Despite correction for variability, the SLCT still proved to be at least 2 times more sensitive than standard tests under most conditions.

DISCUSSION

Like other letter chart tests, the SLCT is easy to administer and easy to score. Despite its apparent simplicity, it offers a sensitive, adjunctive approach for monitoring visual resolution. It uses a forced-choice, letter recognition task, which is not affected by shifts in patient criterion. Important design principles conceived by Bailey and Lovie[7] and Pelli et al.[10] are included in the SLCT. By using a contrast step size of 0.1 log units and 10 letters per line, performance on the SLCT can

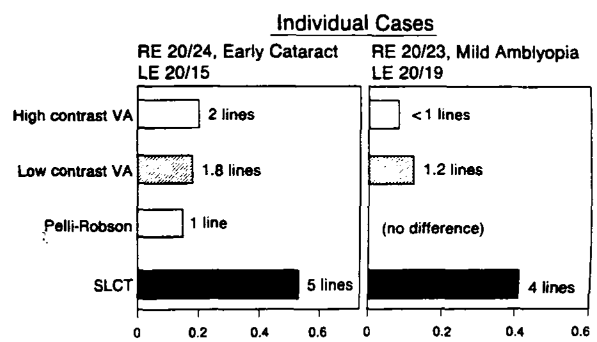

Figure 7. Letter chart test results from two patients: a 56-year-old male with an early nuclear cataract in his right eye (left panel), and a 23-year-old male with mild amblyopia in his right eye (right panel). High contrast VA is shown at the top and the difference in log scores between better and affected eye (LE-RE) is plotted for each vision test. In both cases, there were small differences between eyes with standard tests (1 to 2 lines), but larger differences with the SLCT (4 to 5 lines).

be scored as 0.01 log units per letter, which is 2 times finer than existing tests. The unique feature of the SLCT, the use of small letters to measure CS, exploits the steep slope of the CS function where small changes in VA are associated with large changes in CS (Fig. 1).

Our present results confirm previous findings that small letter CS is more sensitive than standard VA tests to small amounts of blur, modest changes in stimulus luminance, and vision with two eyes compared to one eye.[1–3] These findings, initially revealed with letters generated on a computer monitor, were shown to be valid for the SLCT—a letter chart available for general use. Previous results for spherical blur were confirmed and a similar effect was found for astigmatic blur. A modest reduction in luminance produced a small decrease in VA, but a larger decrease on the SLCT. This effect has been attributed to the quantal nature of light for which decreases in intensity are not matched by proportional decreases in noise.[16, 17] Visual enhancement with two eyes compared to one eye was greater for CS than for standard VA tests, a result also related to the steep slope of the CS function.[14, 15] The greater sensitivity of the SLCT to blur, reduced luminance, and binocular enhancement endured despite correction for variability between- and within-subjects.

Although the SLCT is more sensitive than VA under certain conditions, the range of this test is much more limited than standard tests of VA. Acuity charts include a gamut of letter sizes to assess various levels of resolution, whereas the SLCT offers a refined measure of sensitivity for only a single letter size (4/5 at 4 m). In patients with decreased acuity (<4/5), the SLCT can be administered at a lesser test distance to make letter size larger and thus more appropriate for the acuity level. In the present study we used a constant test distance, but an alternative approach would be to measure VA first, and then adjust viewing distance to the SLCT such that letter size is always a constant multiple of the acuity threshold (e.g., 0.2 log units or 2 lines above measured VA). This would increase the range of patients that could be tested with the SLCT, and assure that measures derive from the descending slope of the CS function where small changes in VA are associated with larger changes in CS. Also, it may be desirable to occlude half the chart and present five letters per line (0.02 log units per letter) to expedite clinical testing.

Several clinical conditions, including early cataract, keratoconus, corneal infiltrates, and mild amblyopia were characterized by subtle reductions in VA, but larger decreases on the SLCT. Although VA provides an adequate measure of resolution in many patients, the cases described here exemplify the potential for using the SLCT when there may be a decrease in central vision undisclosed by conventional testing (e.g., diabetic retinopathy, subtle macular edema, early or resolved optic neuritis). The SLCT may prove useful as an adjunctive test for monitoring vision after refractive surgery (e.g., RK and PRK), and during the course of pharmacologic or vision therapy. As demonstrated in previous studies,[4–6] small letter CS is a sensitive test for identifying visual abilities of pilot trainees, and may be useful in institutional settings to determine whether individuals meet vision standards, or have undergone changes in vision over time. Currently we are using the SLCT and other vision tests to evaluate the effects of age and refractive error on spatial vision of Army aviators.

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