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Luminance Effects on Visual Acuity and Small Letter Contrast Sensitivity

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By

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Luminance Effects on Visual Acuity and Small Letter Contrast Sensitivity

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ABSTRACT

The purpose of this study was to evaluate the effects of luminance on visual acuity (VA) and small letter contrast sensitivity (SLCS). Computer-generated letter charts were used to measure VA and SLCS [6/7.5 (20/25) Snellen equivalent] as a function of stimulus luminance. Letter size (VA) and contrast (SLCS) were varied in equal logarithmic steps, making the task and scoring procedure comparable for the two types of measurement. Both VA and SLCS decreased with decreasing luminance, but the effect was far greater in the contrast domain. Reducing luminance from 116 cd/m² to 0.23 cd/m² produced a 3 × reduction in VA, but a 17 × reduction in SLCS. The greater sensitivity of SLCS to luminance endured even after correction for greater measurement variability. SLCS is a sensitive approach for detecting resolution loss undisclosed by standard measures of VA. It may be useful for monitoring visual loss from light attenuation in early cataracts, and for detecting subtle resolution loss from neural or pathologic factors in ocular and neuro-ophthalmologic disease.

Key Words: visual acuity, contrast sensitivity, luminance, resolution

A number of visual functions, including visual acuity (VA),[1–4] contrast sensitivity (CS),[5–8] and temporal aspects of vision,[9] are dependent on the luminance of the visual stimulus. Typically, the relation between vision and luminance is expressed in terms of the effects on VA. Although decreasing luminance causes a reduction in VA, clinically significant loss of VA does not occur with luminance reductions over much of the photopic range.[3] Often it is tacitly assumed that resolution is normal under moderate to high light levels, but is reduced under lower levels of illumination.

CS also decreases with decreasing stimulus luminance.[5–8] However, because CS typically is measured with moderate spatial frequency stimuli, comparison of CS to VA loss with decreasing luminance is problematic inasmuch as the two measures involve separate mechanisms affected differently by optical and neural factors. Comparison of luminance-related resolution loss between acuity and contrast domains requires stimuli of comparable size.

Recently it was demonstrated that small letter CS (SLCS) is a more sensitive index of defocus than conventional measures of VA.[10] Like VA, SLCS is measured with small letters containing higher spatial frequencies, but the letters are varied in contrast rather than in size. The greater sensitivity of SLCS to defocus is attributed to the steep, descending slope of the CS function for which small changes in VA are associated with larger changes in CS. This concept is illustrated in Fig. 1, which shows that defocus shifts the descending limb of the CS function downward and to the left. The leftward shift along the spatial frequency axis represents the loss of VA. The downward shift along the contrast dimension shows the relatively greater loss of SLCS.

If reducing the luminance of the stimulus affects the CS function in a manner similar to the effects of defocus, then SLCS may prove to be more sensitive than VA to subtle reductions in

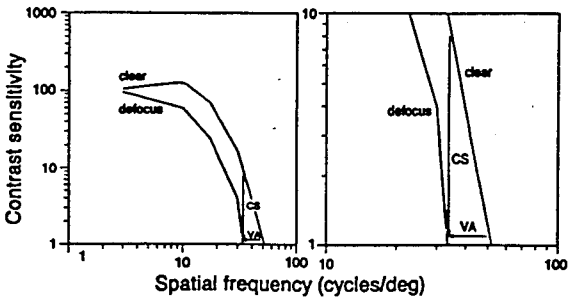

Figure 1. Defocus effects on VA and CS. The left panel shows the CS function with and without defocus, whereas the right panel shows a magnified view of the descending limb. Defocus reduces the contrast of higher spatial frequencies shifting the CS function downward and, consequently, to the left. Because of the steep slope of the descending limb, a reduction in VA is associated with a greater loss of CS, as indicated by the arrow lengths. A similar effect occurs with luminance-induced changes in resolution.

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stimulus luminance. This could have clinical application in that visual loss from light attenuation with early cataracts may be better detected with SLCS. This report compares the effects of luminance reduction on VA to its effects on SLCS. Theoretical factors and clinical applications are considered.

METHODS

VA and SLCS were measured with computer-generated letter charts displayed on a video monitor. Monitor luminance and letter contrast were under software control. The VA and SLCS charts were patterned after those developed by Bailey and Lovie[11] and Pelli et al.,[12] respectively. Each chart consisted of seven rows of letters with five letters per row, and subtended a horizontal visual angle of 3.1°. Two video frames were required to display the entire range of contrasts on the SLCS chart. The VA chart consisted of black, high contrast (93%) letters on a white background. The letters were larger on top, and became progressively smaller, by line, in 0.1 log unit steps with VA ranging from 6/15.1 (20/50.2) to 6/3.8 (20/12.6) (0.4 to -0.2 logMAR). The same principles were used to design the SLCS chart, but letter size was held constant (6/7.5 or 20/25 Snellen equivalent), whereas contrast decreased, by line, in 0.1 log unit steps (from 93% to 5%). As noted in the earlier text, small letters were used to measure CS to: (1) assess 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 larger changes in CS (Fig. 1). The same letters were used on both charts [5 × 4 aspect ratio (height × width) nonserifed letters of about equal visibility[11]], but letter sequence was varied from trial to trial by software control to discourage learning effects. The charts were presented at white background luminances ranging from 0.23 cd/m^2 to 116 cd/m^2 in 0.3 log unit (2×) steps. The different luminances were achieved by placing neutral filters of appropriate optical density in a filter holder directly in front of the subject's eye. Values were specified in terms of the luminance of the white background because it occupied most of the display and probably governed the adaptational state of the eye.[a] The luminances were presented in ascending order to minimize the time required for adaptation, and to discourage learning effects because resolution improves with luminance.

[a] Because mean luminance on a variable contrast chart increases with decreasing contrast (lower contrast letters have higher mean luminance), this variability could influence our results. To explore this possibility, VA and SLCS also were evaluated as a function of the mean luminance of the letter row at which threshold occurred. Results were essentially the same when expressed relative to mean luminance as they were when expressed relative to background luminance.

Subjects were seated 4.8 m from the display in an otherwise dark room. The left eye was occluded with an eye patch, and the subject adapted with the right eye for 6 min to a uniform field displayed on the monitor at the lowest luminance tested (0.23 cd/m^2). This period of adaptation was deemed sufficient because longer periods produced no improvement in VA or SLCS. After adaptation, the VA chart was displayed, and the subject was instructed to start from the top and read each row of the chart as far down as possible. This was followed by SLCS testing. The subject then adapted for 1 min to a uniform field at the next highest luminance followed by measurement of VA and SLCS. This procedure was continued across the entire range of luminances. Scoring was conducted by letter with a precision of 0.02 log units.

VA and SLCS thresholds were obtained from 5 subjects (ages 22 to 39 years). Each subject was refracted to maximum VA and optically corrected during testing. Informed consent was obtained from all subjects after protocol approval by our institutional review committee.

RESULTS

Fig. 2 shows mean (±1 SE) VA (left) and SLCS (right) plotted as a function of stimulus luminance. By displaying the results on scales that span equivalent logarithmic ranges, the magnitude of the effect can be compared directly between acuity and contrast domains. Both VA and SLCS improve with increasing luminance, a finding that is well established from previous studies. However, the magnitude of this effect is far greater in the contrast domain (Friedman nonparametric two-way analysis of variance, $\chi^2 = 16$, $p < 0.001$). Increasing the luminance from 0.23 to 116 cd/m^2 produces a 3× increase in VA, but a 17× increase in SLCS. With each 2× increase in luminance, VA increases 10%, an improvement of two letters on the acuity chart, whereas SLCS

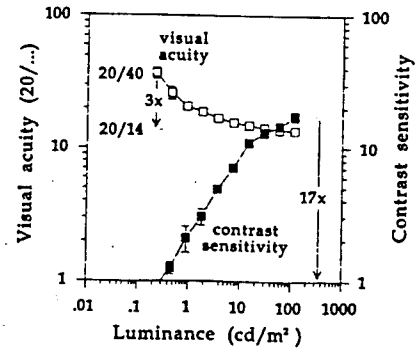

Figure 2. Mean (±1 SE) VA and SLCS (20/25 letter size) are plotted against the luminance of the letter chart. Values are shown on logarithmic axes which span equivalent ranges (100× change in visual threshold). For the range of luminances tested, VA changes 3×, whereas SLCS changes 17× (20/40 = 6/12 and 20/14 = 6/4.2).

increases 40%, an improvement of 1½ lines on the contrast chart.

Although changes in luminance have a greater impact on SLCS than on VA, the significance of this finding depends on the variability of the measurement. A larger effect does not ensure greater sensitivity if the measurement is more variable, as is the case for SLCS. To standardize measurements with respect to variability, the difference between each visual threshold and the mean threshold at maximum luminance was divided by the standard deviation (SD) of the measurement. This transformation, which specifies all scores as SD's from the mean, allows for direct comparison of VA and SLCS results. Means and SD's (logMAR: -0.15 ± 0.05; logCS: 1.20 ± 0.08) were from a previous study,[10] which used a larger sample size that better approximated a normal distribution. Fig. 3 shows the average number of SD's from the mean (at 116 cd/m^2) plotted against luminance for VA and SLCS. Using a conservative criterion of 3 SD's from the mean performance at maximum luminance (116 cd/m^2), SLCS is significantly reduced at 10 cd/m^2, whereas VA is not significantly reduced until the luminance is decreased to 1 cd/m^2, a 10× lower luminance. Thus, even when correction is made for variability, SLCS still provides a more sensitive index of subtle changes in the luminance of the visual stimulus, and this effect is highly significant (Friedman two-way analysis of variance, $\chi^2 = 18$, $p < 0.001$).

Despite the larger reduction in SLCS with decreasing luminance, the origin of this effect remains unclear. Although optical factors, such as pupil dilation and increased accommodation (night myopia), contribute to the reduction in vision with decreasing luminance, research suggests that these effects are most detrimental at luminances lower than those used in the present study.[4] To explore this issue, measurements were repeated on one subject who viewed the display through a 3-mm artificial pupil to minimize optical effects. Values were compared to those made with the subject's natural pupil, but equated for retinal illuminance. A significantly greater reduction in vision with the larger (natural) pupil would indicate that optical factors mediate this effect. Although VA and SLCS were consistently better with the artificial pupil, the overall reduction in performance with decreasing retinal illuminance was about the same for artificial and natural pupils (Table 1), and the slope of this reduction also was comparable for the two conditions. Thus, for the range of luminances tested in the present study, the reduction in visual resolution cannot be attributed to optical factors.

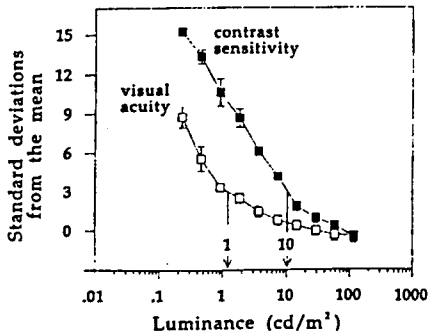

Figure 3. The average number of SD's from mean performance at maximum luminance (116 cd/m^2) is plotted against chart luminance for VA and SLCS.

DISCUSSION

The results of this study demonstrate that SLCS provides a sensitive index of changes in the luminance of the stimulus. Luminance reductions in the photopic range produced large losses in SLCS with minimal degradation of VA. Reducing the light level 100× (from 100 to 1 cd/m^2) produced an 8× reduction in SLCS, whereas VA remained normal by clinical standards [6/6 (20/20)].

It could be argued that comparison of VA and SLCS is not entirely valid because the two tests measure different aspects of visual function. Several approaches were used in this study, which mitigate against this criticism and facilitate comparison between acuity and contrast domains. First, by using letter charts of comparable design, with equal log steps of acuity and contrast, interval size and scoring were the same for the two measures. Second, small letters were used to assess both VA and SLCS, making it likely that thresholds were determined by comparable spatial frequency channels. Third, by standardizing all scores with respect to variability, VA and SLCS were expressed in equivalent units, making a more direct comparison possible. Despite greater variability, SLCS still proved to be a more sensitive index of changes in resolution with luminance.

The reduction in resolution observed with decreasing luminance could reflect optical factors such as pupillary dilation, aberrations, or inaccurate accommodation. However, previous research[4] and the results of our control experiment (Table 1) indicate that optical factors cannot explain the decline in VA and SLCS over the range of luminances tested. Hence this reduction apparently is linked to the decrease in retinal illuminance. It is noteworthy that SLCS varied in proportion to the square root of retinal illuminance, a finding which has been attributed to the quantal

TABLE 1. Decrease in visual performance with reduction in retinal illuminance.

Vision Test	Log Decrease in Visual Performance with Reduction in Retinal Illuminance (823–1.6 Td)	
	Natural pupil	Artificial pupil (3 mm)
Visual acuity	0.39 log units	0.36 log units
Contrast sensitivity	1.24 log units	1.18 log units

nature of light,[13, 14] and which has been reported for human and ideal observers limited only by photon noise.[6, 7, 14]

The greater reduction of SLCS than VA with decreasing luminance is of clinical interest because it suggests that SLCS is more sensitive to conditions that attenuate light to the central retina. Subtle visual reduction caused by light attenuation from early cataracts may be better detected, monitored, and correlated with symptoms by measuring SLCS. Diseases of the retina or optic nerve that reduce visual efficiency in a manner comparable to light attenuation also may be more readily detected by measuring resolution in the contrast domain. Further testing of SLCS in clinical populations is needed to validate these assumptions. We are currently developing a hard copy version of the small letter contrast test for widespread distribution.

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