Influence of Stiles–Crawford apodization on visual acuity

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Received July 16, 2001; revised manuscript received December 6, 2001; accepted December 6, 2001

The Stiles–Crawford effect (SCE) of the first kind has often been considered to be important to spatial visual performance in that it ameliorates the influence of defocus and aberrations. We investigated the influence of SCE apodization on visual acuity as a function of defocus (out to ±2 D) in four subjects. We used optical filters, conjugate with the eye's entrance pupil, that neutralized or doubled the existing SCE. With an illiterate-E task, the influence of the SCE was more noticeable for myopic defocus than for hypermetropic defocus, was generally more noticeable for high-contrast than for low-contrast letters, and increased with increase in pupil size. The greatest influence on visual acuity of neutralizing the SCE, across the subjects and range of conditions, was deterioration of 0.06 (4-mm pupil), 0.16 (6-mm pupil), and 0.29 log unit (7.6-mm pupil).

OCIS codes: 330.1070, 330.5370.

1. INTRODUCTION

Light passing through the periphery of the pupil does not appear as bright as light passing through the pupil near its center.[1] This is well known as the Stiles–Crawford effect (SCE) of the first kind and is caused by the waveguide nature of the retinal photoreceptors and in particular the cones.[2] Its extent is a combination of the directional properties of individual receptor inner segments, relative orientation of different receptors, and leakage of light between cones (cross talk).[3]

The SCE is important in photometry because it affects retinal adaptation. In many visual experiments using different pupil sizes for which it is considered important to keep similar retinal adaptations, compensation has been made for the SCE. This can be done with equations developed by Le Grand[4] and Martin.[5] These apply to the SCE peak when it coincides with the pupil center, but allowance for decentration of the SCE peak can be easily made.[6]

The SCE is considered also to be important to spatial visual performance in that it ameliorates the influence of defocus and aberrations when pupils are large,[7] and it has often been "invoked" when simple geometric predictions of the effects of aberrations and defocus are not supported by experimentation.[8,9] It has been cited as being a component of the Campbell effect,[10] which is the loss in visual acuity when small artificial pupils are decentered in front of the eye.[11] There have been some theoretical investigations of the influence of the SCE on the modulation transfer function (MTF), in which the SCE is modeled as a pupil apodization,[12] which indicate that the influence of the SCE on spatial visual performance is likely to be small[13–16]; however, one study predicted large effects for 8-mm pupils.[17]

There have been few experimental investigations of the SCE's influence on visual performance. Rynders[18] investigated the influence of the SCE on transverse chromatic aberration, the contrast sensitivity function, and depth of focus. More correctly, he investigated the SCE apodization model of the SCE, using optical filters that when placed conjugate with the eye's pupil neutralized the SCE.[18,19] He found that the filters largely reversed the decrease in slope of the transverse aberration versus pupil position obtained with large pupils. However, Atchison and Scott[20] could not reproduce this finding. One of Rynders' subjects showed a decrease in contrast sensitivity, when the SCE was neutralized, of up to 0.4 log unit (10 cycles/degree, 7-mm pupil), but generally the decreases were closer to 0.3 log unit. For two other subjects with 5-mm pupils, the influence of the SCE was generally less than 0.2 log unit. The first subject also showed a small decrease in depth of focus for larger pupil sizes when the SCE was neutralized, but this was not seen in two other subjects.

Visual acuity is a widely used way to evaluate spatial vision and, unlike the (monochromatic) contrast sensitivity function, is influenced by phase effects. Following on from Rynders's experimental studies of contrast sensitivity and the SCE,[18,19] we have investigated the influence of SCE on visual acuity across a range of simulated refractive errors. We have used the apodization model of the SCE, since we are manipulating the SCE with optical filters.

2. METHODS

A. Subjects

The right eyes of four subjects in good ocular and general health were used. Eyes were cyclopleged with 1 drop of 1% cyclopentolate, with an additional drop applied approximately every 2 h. Preliminary data were collected on the right eyes of subjects NS and PA. Most data were collected for subjects DAA (−2.00 DS) and DHS (+0.75 DS/−0.50 DC × 180). The astigmatisms of the eyes of DHS and NS were corrected with trial lenses conjugate with the cornea during visual acuity measurements.

B. Measuring and Correcting the Stiles–Crawford Effect

The apparatus has been described in detail elsewhere,[20] and only a brief description is given here. It was a two-channel Maxwellian-viewing system imaging two light sources via a −1× relay system to the subject's entrance pupil. The light sources were 1.0-mm pinholes illuminated by diffuse green diodes, with a peak radiant intensity at 565 nm and a dominant wavelength of approximately 575 nm for a range of standard illuminants. The illuminance of this field was approximately 93 trolands. A reference source provided a background field of 7 deg, entering the eye in the middle of the pupil. The test source was electronically square-wave flickered at 2 Hz and provided a 0.6-deg field. The entry position of the test source was computer controlled by stepper motors. The source gave bursts of 250-ns pulses every 5 ms, with the illuminance being varied by the number of these pulses over a 4-log-unit range. Threshold was obtained with a descending method of limits by use of a button module.

Forty-nine positions across a 6-mm diameter pupil were assessed in 0.75-mm intervals. Four measurements were taken at each position. The subject's head position was fixed with a bite bar under *XYZ* movement control. An illumination ring containing infrared light-emitting diodes was used to align the eye. A video camera linked to a monitor provided a view of the subject's pupil. The eye was centered by using the pupil center. The experimenter viewed the monitor and adjusted the bitebar as necessary to maintain pupil alignment to within 0.1 mm during measurements.

After measurements were taken, a least-squares-fit program used the means (in log units) to obtain function fits of the form

$$\eta(x, y) = \eta(x_{\max}, y_{\max}) \times \exp[-\rho_x(x - x_{\max})^2 - \rho_y(y - y_{\max})^2], \tag{1}$$

where $\eta(x, y)$ is the sensitivity at any position (x, y) in the entrance pupil, $(x_{\max}, y_{\max})$ is the peak of the SCE function relative to the center of the entrance pupil, $\eta(x_{\max}, y_{\max})$ is the sensitivity at the peak of the SCE function, and ρ_x and ρ_y are SCE coefficients in the x and y directions. Positive values of $x_{\max}$ and $y_{\max}$ indicate nasal and superior positions, respectively, of the peak relative to the center of the pupil. 95% confidence intervals were obtained for each of the parameters, and a correlation coefficient was obtained for the overall fit.

Using the function fits, we made optical filters from photographic film[21] to neutralize and approximately double the SCE for each subject. The accuracy of these filters was checked by both photometric measurements and by redetermining the SCE with the filters carefully positioned immediately in front of the 1-mm test aperture. The SCE-neutralizing filters had low transmittances corresponding to SCE peaks (e.g., 3.2% DAA, 6.1% DHS).

During experiments the filters were placed immediately in front of the position of the test source so that they were conjugate with the pupil of the eye. Accuracy of alignment was ±0.1 mm.

C. Aberrations and Retinal Image Reconstruction

Monochromatic aberrations of our subjects were measured by using subjective vernier alignment with a system less sophisticated than, but similar to, that described by He *et al.*[22] It was based on the SCE apparatus. Light from a reference target passed through the whole of the subject's pupil, and light from a test target passed through another, variable, pupil location. If there was no aberration of the ray bundle from the test target, the targets appeared aligned when they had the same location in object space. If there was aberration of the ray bundle from the test target, the targets did not appear aligned. The transverse movement of the test target necessary to achieve apparent alignment was then a measure of transverse aberration.

The apparatus is shown in Fig. 1. The reference target was a 12-arc-min annulus, 0.5 arc min wide, illuminated by a quartz halide source through a diffusing filter, RF. The test target was a spot on a cathode-ray oscilloscope, CRO, which was viewed through a 1.0-mm-diameter aperture, $Ap_{1.0}$. Both targets were made monochromatic by 550-nm green interference filters, IF's placed in the optical paths (full width at half-maximum was 10 nm). For any location of the aperture, the subject's task was to move the spot under joystick control so that it appeared in the middle of the ring.

The targets were 5.0 m from $Ap_{1.0}$. The aperture was imaged onto the eye's entrance pupil, EP, by a relay system, L_1 and L_2. The paths from the test and reference targets joined at the pellicle beam splitter, PBS_1, placed between the aperture and the first of the lenses (L_1). Other details regarding head stabilization, eye monitoring, and refractive error correction were the same as described for the SCE apparatus.

At the start of a session, the oscilloscope was calibrated. A pattern of points appeared, including the corners and the center of the range of pixel positions (−128, −128) to (127, 127). The pattern size was adjusted to be 8 cm on each side. This pattern was replaced by the center spot (CRO coordinates 0, 0). The subject adjusted the orientation of the mirror on the reference target's optical path so that the reference target appeared to move until centered on the spot.

In the experiment proper, the aperture moved on a stage with $x-y$ movements into the various test locations. The typical pattern of pupil positions was 49 positions across a 6-mm-diameter pupil. This 6 mm represented the maximum separation of aperture centers, so in all a 7-mm pupil was covered. Usually, four measurements were taken at each position, from which the means in the x and y directions were taken. A program used the transverse-aberration results to determine the Zernike aberration coefficients across the pupil.

Radial MTFs were obtained at -2 D, 0 D, and $+2$ D defocus. These were done as monochromatic MTFs at the reference wavelength (550 nm) and as polychromatic MTFs based on wavelengths from 460 to 640 nm in 30-nm steps. For the latter, we assumed an equi-energy light source (the monitor used in the visual acuity experiments was a reasonable approximation to this) and weighted the results by the V_λ function. As we did not have aberration measurements at different wavelengths, we assumed that the aberration coefficients apart from defocus did not change with wavelength when expressed in distance units. Also, we assumed the SCE did not change as a function of wavelength. Using the chromatic eye model of Thibos *et al.*,[23] we modified the defocus coefficient at each wavelength. We did not take into account any foveal transverse aberration chromatic aberrations in this modeling. The influence of this omission was expected to be small, as the subjects' visual axes were displaced horizontally in the pupil by ~0.1 mm from the line of sight,[20] corresponding to transverse chromatic aberration between 460 and 640 nm of less than 0.1 arc min.[24]

With propriety software (Zemax), simple model eyes were constructed containing a wave-front phase surface that matched the determined aberrations, and the diffraction images of monochromatic letter E's were calculated.

D. Visual Acuity

The apparatus for measuring aberrations was modified (Fig. 1). The beam splitter, PBS_1, was removed, the 1.0-mm aperture $Ap_{1.0}$ was replaced by other apertures Ap (4, 6, or >7.6 mm), and the cathode-ray oscilloscope was replaced by a Sony Triniton Multiscan 200PS monitor (Mo_2 in Fig. 1). In the experiment the monitor was used with all three guns, i.e., white light, or with just the green gun (mean wavelength of 545 nm and full width at half-maximum luminance height of 62 nm).

Additional neutral density filters, ND, were determined and were used to give the SCE-normal and SCE-doubling conditions effective luminances similar to those for the SCE-neutralizing condition. The precision of matching was ±0.1 log unit. The neutral density filters necessary to match the SCE-neutralized condition gave effective luminances at the two main subjects' eyes as follows: DAA, 4-mm pupil, white background 5.0 cd/m^2; DAA, 6-mm pupil, white background 6.5 cd/m^2; DAA, 7.5-mm pupil, white background 8.2 cd/m^2; DAA, 6-mm pupil, green background 6.9 cd/m^2; DHS, 6-mm pupil, white background 14.4 cd/m^2.

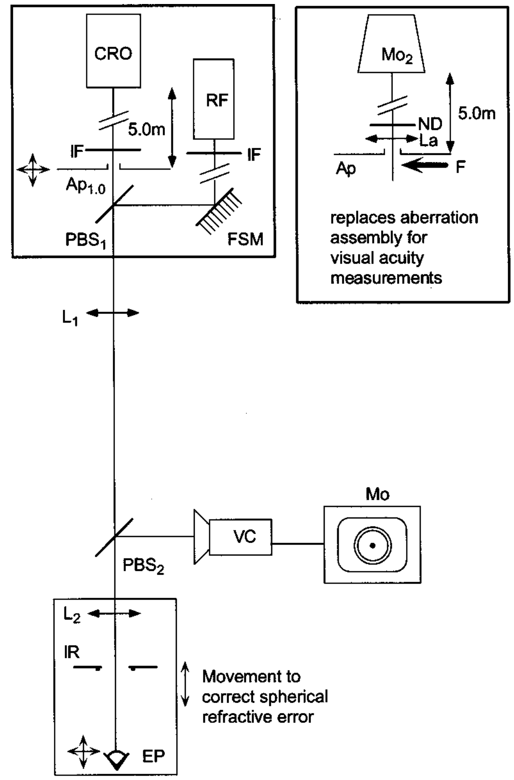

Fig. 1. Apparatus for measuring aberrations of the eye by a subjective vernier alignment technique, SCE and its adaptation for measuring visual acuity. PBS_1 and PBS_2, 90/10 pellicle beam splitters; L_1 and L_2, relay lenses; IR, illumination ring, FSM, front-surface mirror; VC, video camera; Mo_1, monitor; EP, entrance pupil of eye; $Ap_{1.0}$, 0.5-mm aperture; IF, 550-nm interference filters; CRO, cathode ray oscilloscope; RF, light source, diffuser, and reference target. Additional items for visual acuity: ND, neutral density filters; La, lenses to correct astigmatism; Ap, 4-mm, 6-mm or >7.6-mm apertures; Mo_2, Sony Triniton monitor; F, position of SCE-neutralizing and SCE-doubling filters.

For the SCE-normal condition, each subject viewed a white 0.1-logmar E letter (equivalent to 6/7.5 or 20/25) and adjusted the position of a Badal optometer (eye and the relay lens nearer to the eye) until the letter was seen clearly. This was done by approaching the point of clarity from both directions 3 or 4 times each and taking a mean. This was taken to be the in-focus position (it was also used for taking the aberration measurements). To produce various levels of defocus, the Badal optometer was moved toward or away from the monitor to induce negative (hypermetropic) or positive (myopic) defocus, respectively. For the SCE-normal condition, the two main subjects also viewed a green 0.1-logmar E letter. Its in-focus position was used as the basis of monochromatic MTF calculations and retinal image reconstruction (Subsection 2.C). This in-focus position was within 0.3 D of the white light in-focus position for both subjects.

The subjects performed a four-alternative forced-choice illiterate-E experiment for both high- (97%) and low- (16%) contrast letters and for a defocus range of $+2$ D to -2 D. They pressed one of four buttons on a keyboard to indicate letter orientation following a 1-s presentation. One hundred and sixty presentations were given in a run across a 0.4-log-unit range (5 presentations × 4 letter

Table 1. Measured SCE Functions for Subjects (Wavelength 575 nm), Showing Mean and 95% Confidence Limits

Subject	Run No.	η_{max}	ρ_x	ρ_y	x_{max}	y_{max}	$R^2_{adjusted}$
DAA	1	129 ± 6	0.105 ± 0.013	0.077 ± 0.013	+0.93 ± 0.17	−0.60 ± 0.16	0.953
	2	127 ± 5	0.129 ± 0.015	0.100 ± 0.015	+0.51 ± 0.14	−0.60 ± 0.14	0.949
DHS	1	241 ± 12	0.083 ± 0.013	0.110 ± 0.012	+0.58 ± 0.13	+0.32 ± 0.09	0.918
	2	204 ± 12	0.088 ± 0.015	0.108 ± 0.015	+0.61 ± 0.16	+0.30 ± 0.11	0.891
	3	249 ± 14	0.076 ± 0.014	0.104 ± 0.014	+0.58 ± 0.17	+0.31 ± 0.10	0.887
NS	1	235 ± 15	0.110 ± 0.015	0.118 ± 0.015	+0.47 ± 0.12	+0.21 ± 0.10	0.901
PA	1	217 ± 24	0.101 ± 0.020	0.102 ± 0.020	−0.54 ± 0.19	−0.18 ± 0.16	0.743

Table 2. Measured Neutralizing and Doubling Filters (Wavelength=550 nm)

Subject	Filter Condition	ρ_x	ρ_y	x_{max}	y_{max}	R^2
DAA	SCE-neutralizing					
	Design	−0.120	−0.100	+0.6	−0.6	–
	Measured	−0.120	−0.103	–	–	0.990
	SCE-doubling					
	Design	0.120	0.120	+0.6	−0.6	–
	Measured	0.124	0.120	–	–	0.992
DHS	SCE-neutralizing					
	Design	−0.080	−0.100	+0.6	+0.3	–
	Measured	−0.078	−0.100	–	–	0.998
	SCE-doubling					
	Design	0.120	0.120	+0.6	+0.3	–
	Measured	0.115	0.112	–	–	1.000
NS, PA	SCE-neutralizing					
	Design	−0.100	−0.100	–	–	–
	Measured	−0.098	−0.099	–	–	0.992

Table 3. Subjects' SCE Measurements with Neutralizing and Doubling Filters, Showing Mean and 95% Confidence Limits

Subject	Filter Condition	Run No.	ρ_x	ρ_y	x_{max}	y_{max}	$R^2_{adjusted}$
DAA	SCE-neutralize[b]	1	0.0028 ± 0.021	0.012 ± 0.021	−12.2 ± 90.4	−1.91 ± 3.62	0.352
		2	0.0093 ± 0.017	0.006 ± 0.017	−3.17 ± 5.81	+5.75 ± 15.2	0.565
	SCE-doubled	ideal[a]	0.244	0.220	+0.6	−0.6	
		1	0.223 ± 0.023	0.219 ± 0.023	+0.68 ± 0.10	−0.82 ± 0.11	0.964
		2	0.220 ± 0.020	0.200 ± 0.020	+0.50 ± 0.08	−0.66 ± 0.10	0.963
DHS	SCE-neutralize[b]	1	0.00016 ± 0.015	0.012 ± 0.013	−89 ± 8533	−1.69 ± 2.05	0.340
		2	0.00028 ± 0.017	0.012 ± 0.017	+63.5 ± 3854	−0.81 ± 1.52	0.149
	SCE-doubled	ideal[a]	0.195	0.212	+0.6	+0.3	
		1	0.189 ± 0.012	0.209 ± 0.012	+0.60 ± 0.06	+0.42 ± 0.05	0.984
		2	0.178 ± 0.013	0.214 ± 0.05	+0.66 ± 0.07	+0.21 ± 0.05	0.976

[a] Ideal is $\rho_x = \rho_y = 0$.
[b] Determined by subtracting design SCE-neutralizing filter from measured SCE-doubling filter in Table 2.

orientations × 8 sizes). Most runs lasted 4–6 min. Three to seven runs were done for each combination of subject, defocus, contrast, and SCE condition, with alternation in the order of SCE condition for each defocus/contrast combination. The data were fitted with probit functions, and the 50% probability level (after correction for guessing) was taken as the measure of visual acuity.

We anticipated that relative to the SCE-normal condition, the SCE-neutralizing condition would decrease visual acuity while the SCE-doubling condition would improve it because of the amelioration of the effects of defocus and aberration provided by the SCE. However, the reduction in effective retinal illuminance provided by the SCE can be expected to counteract this effect. The results from the experiment provide an unfair comparison between the conditions because they were measured at similar effective retinal illuminances. We took this into account by making corrections to visual acuity for the SCE-neutralizing and SCE-doubling filters' effective retinal illuminances. First we calculated the photometric efficiency of a pupil of radius R_p,[6] which for the form of the SCE given by Eq. (1) is

$$E(R_p) = \frac{\displaystyle\int_{-R_p}^{+R_p}\int_{-\sqrt{R_p^2-x^2}}^{+\sqrt{R_p^2-x^2}} \exp[-\rho_x(x - x_{\max})^2 - \rho_y(y - y_{\max})^2]\mathrm{d}y\,\mathrm{d}x}{\pi R_p^2}. \quad (2)$$

Second, we performed an experiment in which we determined visual acuity as a function of luminance for the SC-normal condition, with the range of luminances being from the maximum level possible to a level below that used for the main experiment. The photometric efficiencies were combined with the rates of change of visual acuity per change in luminance to provide corrections to the data.

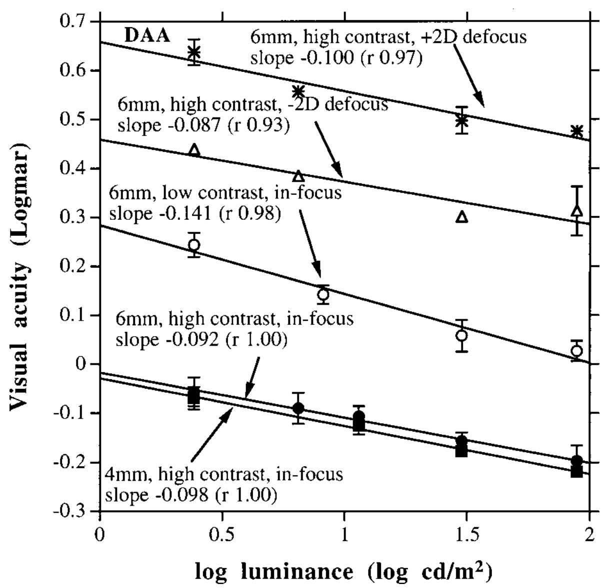

Fig. 2. Visual acuity as a function of luminance for subject DAA for letters on a white background in the following situations: in-focus, 6-mm pupil, and high-contrast letters; in-focus, 6-mm pupil, and low-contrast letters; in-focus, 4-mm pupil, and high-contrast letters; +2 D defocus, 6-mm pupil, and high-contrast letters; −2 D defocus, 6-mm pupil and high-contrast letters. Slopes and correlation coefficients of linear fits are given.

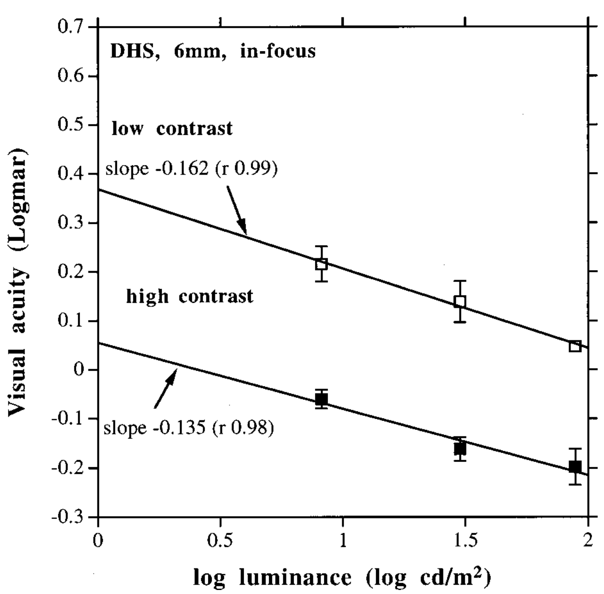

Fig. 3. Visual acuity (Logmar) as a function of luminance (cd/m^2) for subject DHS for 6-mm pupils, in-focus, and both high- and low-contrast letters on a white background. Slopes and correlation coefficients of linear fits are given.

To compare between filter conditions, we conducted unpaired, two-tailed t tests at the 95% level of significance.

3. RESULTS

A. Stiles–Crawford-Effect Measurements and Filters

Table 1 shows SCE functions for subjects for 1–3 runs.[25] These are of near average steepness,[26] and the peaks are relatively close to the pupil centers. Parameters with neutralizing and doubling filters are given in Table 2. SCE functions with filters for DAA and DHS are shown in Table 3; the measured functions are close to the ideal functions.

B. Visual Acuity versus Luminance

Figure 2 shows visual acuity as a function of luminance for subject DAA in the SCE-normal condition for a variety of situations: 6-mm pupil, high-contrast, in-focus; 6-mm pupil, high-contrast, +2 D defocus; 6-mm pupil, high-contrast, −2 D defocus; 6-mm pupil, low-contrast, in-focus; 4-mm pupil, high-contrast, in-focus. The results are well fitted by linear log–log plots across the luminance range. All the situations with high-contrast letters produced a loss in visual acuity of approximately 0.010 log unit for each 0.1 log unit decrease in luminance. The 6-mm pupils with low-contrast letters had a greater loss in visual acuity of approximately 0.014 log unit for each 0.1-log-unit decrease in luminance.

Figure 3 shows similar results for subject DHS for 6-mm pupils and in-focus high- and low-contrast letters. He had greater rates of visual acuity change than did DAA for high-contrast letters (0.013 for each 0.1-log-unit decrease in luminance for high-contrast letters), and these slopes changed little with decrease in contrast.

As described in Subsection 2.D, these results were used to make corrections to the results in the main experiment. These corrections are shown in Table 4.

C. Visual Acuity for the Different Filter Conditions

Figure 4 shows visual acuity as a function of defocus for the two main subjects in the various combinations of conditions. Mean differences between the conditions of >0.050 log unit (lu) were always statistically significant, and we have adopted a difference of 0.050 lu as a practical level of significance in our results. In the figure, differences between SCE-neutralized and SCE-normal conditions >0.050 lu are indicated by asterisks, and differences between SCE-doubled and SCE-normal conditions >0.050 lu are indicated by double asterisks.

The majority of experimental work was done with subject DAA. His high-contrast results for 4-, 6-, and

Table 4. Visual Acuity Corrections for the Effective Retinal Illuminance Differences of the Various SCE Conditions[a]

Filter Condition	Pupil Diameter and Letter Contrast	Visual Acuity Correction (log arc min)
SCE-neutralized	4-mm, high-contrast	−0.01 (DAA)
	6-mm, high-contrast	−0.02 (DAA, DHS)
	6-mm, low-contrast	−0.03 (DAA, DHS)
	7.5-mm, high-contrast	−0.03 (DAA)
SCE-doubled	4-mm, high-contrast	+0.01 (DAA)
	6-mm, high-contrast	+0.02 (DAA) +0.03 (DHS)
	6-mm, low-contrast	+0.03 (DAA, DHS)
	7.5-mm, high-contrast	+0.03 (DAA)

[a] Initials in parentheses indicate subjects for which the corrections are applicable.

7.6-mm pupils are shown in Figs. 4(a)–4(d). For a 4-mm pupil and a white background [Fig. 4(a)], only at +2 D defocus was the SCE-neutralized condition worse than the SCE-normal condition at 0.06 lu. For a 6-mm pupil and a white background [Fig. 4(b)], the SCE-neutralized condition was worse than the SCE-normal condition at −2 D defocus (0.09 lu), +1 D defocus (0.11 lu) and +2 D defocus (0.15 lu). In addition, the SCE-doubled condition was better than the SCE-normal condition at +2 D defocus (0.06 lu). For a 7.6-mm pupil and a white background [Fig. 4(c)], the SCE-neutralized condition was worse than the SCE-normal condition for in-focus (0.06 lu) and all positive defocus levels up to a maximum of 0.29 lu at +1.5 D defocus. In addition, the SCE-doubled condition was better than the SCE-normal condition at −2 D (0.06 lu) and all positive defocus levels (maximum 0.12 lu at +1.5 D).

For a 6-mm pupil and a green background [Fig. 4(d)], the SCE-neutralized condition was worse than the SCE-normal condition at −2 D defocus (0.07 lu), in-focus (0.08 lu), +1 D defocus (0.16 lu) and +2 D defocus (0.16 lu). The SCE-doubled condition performed better than the SCE-normal condition at +2 D defocus (0.13 lu). The influence of the SCE appears to be greater with a green background than with a white background [compare Figs. 4(b) and 4(d)].

Figures 4(b) and 4(e) show results of our two main subjects with 6-mm pupils, white backgrounds, and both high-contrast and low-contrast letters. The largest differences between SCE-neutralized and SCE-normal conditions were 0.15 lu for DAA [Fig. 4(b)] and 0.08 lu for subject DHS [Fig. 4(e)]. For the subjects, the differences between conditions were generally greater with high-contrast than with low-contrast letters and also were always greater with positive defocus than with negative defocus of the same degree.

To summarize the results, the influence of the SCE is generally small, it increases with increase in pupil size, it is greater with positive than with negative defocus, and it is possibly greater for a near-monochromatic background than for a white background (subject DAA).

As mentioned in Subsection 2.A, preliminary data were collected for two subjects, NS and PP. These were for the SCE-normal and SCE-neutralized conditions with 6-mm pupils, for in-focus and +1 D and −1 D defocus. The results showed the same trend as for the two main subjects. However, when the Table 4 corrections for subject DAA were applied to the results, the only data reaching the 0.05 lu "significance" level were for subject PA at +1 D defocus with high-contrast (0.07 lu) and low-contrast (0.05 lu) letters. As these differences were for single runs, no actual significance can be given to them, but they support assertion that the SCE has a small influence on visual acuity at pupil sizes expected under photopic lighting levels.

4. DISCUSSION

A. Influence of the Stiles–Crawford Effect

By both neutralizing and doubling the SCE with apodizing filters, we have shown that it influences visual acuity for both in-focus and out-of-focus conditions. As expected, this influence increases as pupil size increases. For one subject's 4-mm pupil, the SCE apodization had a small influence only at +2 D defocus and at high contrast. For a 6-mm pupil, the SCE apodization's maximum influences for defocus out to ±2 D were approximately 0.10 and 0.16 lu for our two main subjects and can be considered to be becoming important. Considerable influence of the normal SCE for one subject's fully dilated (7.6-mm) pupil occurred with positive defocus, amounting to nearly 0.3 lu.

It is important to consider whether many people have the combination of sufficiently large pupils and sufficiently high SCEs for these results to indicate that the SCE matters with respect to visual acuity. Atchison and Smith[27] provided a figure summarizing some studies of pupil diameter as a function of luminance level for uniformly illuminated fields. There was considerable variation between studies and within experimental studies. Taking a lower photopic limit of 10 cd m^{-2}, pupil size at this luminance was determined to be 3 mm (curves fitted to previous data[28,29]), 3.5 mm,[30] and 6 mm.[31,32] Alternatively, a mean pupil size of 6 mm was attained when the luminance was approximately 0.003–0.03 cd m^{-2} (Refs. 28–30) and 10 cd m^{-2} (Refs. 31 and 32). Reeves's studies[31,32] clearly give much larger estimates of pupil sizes at any luminance than do the other studies. There are several factors that will influence pupil size and that are not always mentioned in the studies. One of these is subject age, and it is likely that Reeves tested only young subjects, for whom pupil sizes are larger than for older subjects.[33–38] On the basis of these results, a 6-mm pupil seems near the upper limit of pupil sizes that are likely to occur naturally in the photopic luminance levels for which the SCE is at its maximum. However, it is quite likely that some young people may have pupils larger than this, particularly in clinical examinations that use projector or internally illuminated visual acuity charts in otherwise darkened rooms. Thus our results indicate that the SCE is important to visual acuity for at least some people under some lighting conditions.

To pursue the point raised in the previous paragraph, the SCE may still be important at mesopic luminances if it remains at a sufficiently high level. There are little

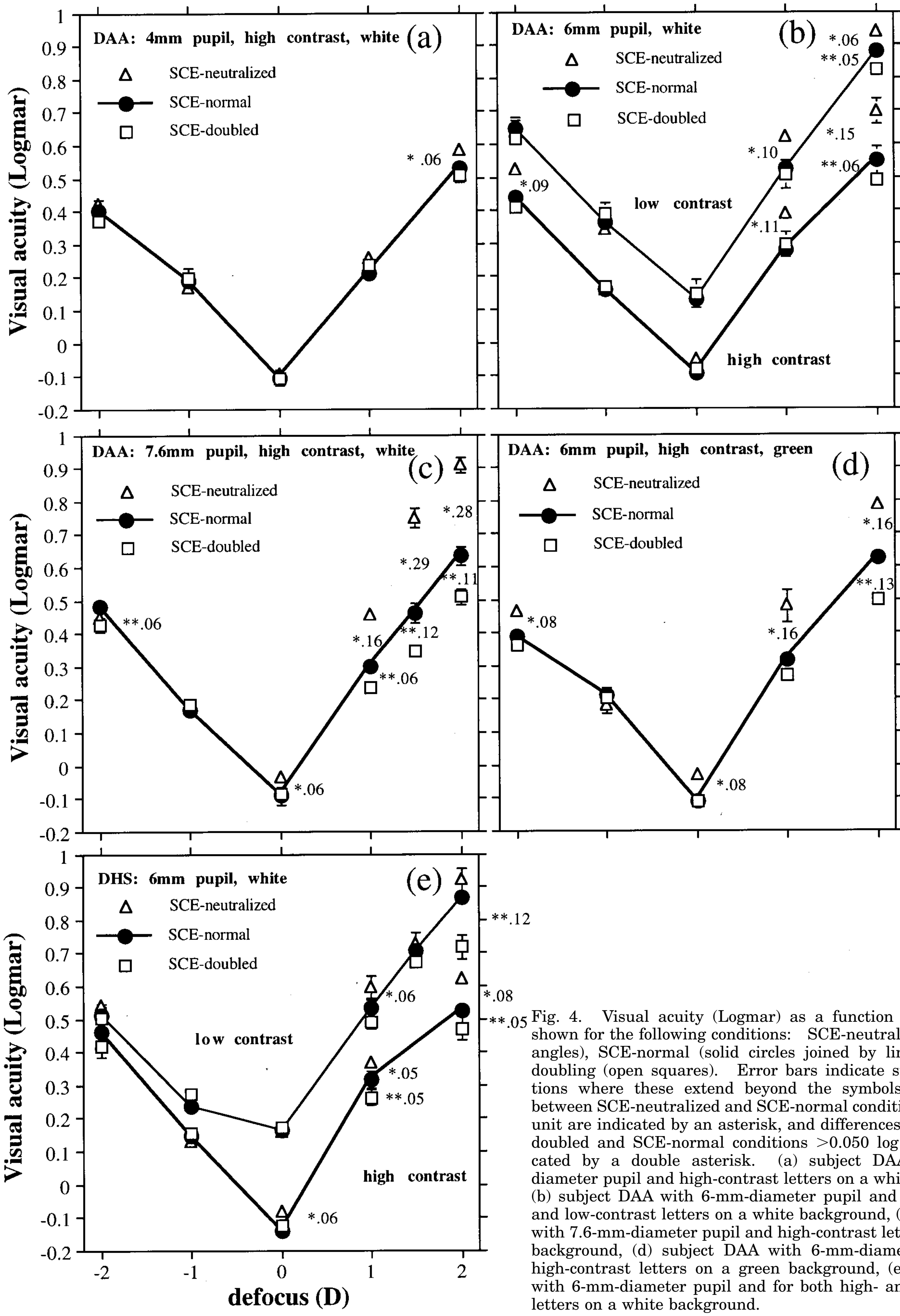

Fig. 4. Visual acuity (Logmar) as a function of defocus (D) shown for the following conditions: SCE-neutralizing (open triangles), SCE-normal (solid circles joined by lines) and SCE-doubling (open squares). Error bars indicate standard deviations where these extend beyond the symbols. Differences between SCE-neutralized and SCE-normal conditions >0.050 log unit are indicated by an asterisk, and differences between SCE-doubled and SCE-normal conditions >0.050 log unit are indicated by a double asterisk. (a) subject DAA with 4-mm-diameter pupil and high-contrast letters on a white background, (b) subject DAA with 6-mm-diameter pupil and for both high- and low-contrast letters on a white background, (c) subject DAA with 7.6-mm-diameter pupil and high-contrast letters on a white background, (d) subject DAA with 6-mm-diameter pupil and high-contrast letters on a green background, (e) subject DHS with 6-mm-diameter pupil and for both high- and low-contrast letters on a white background.

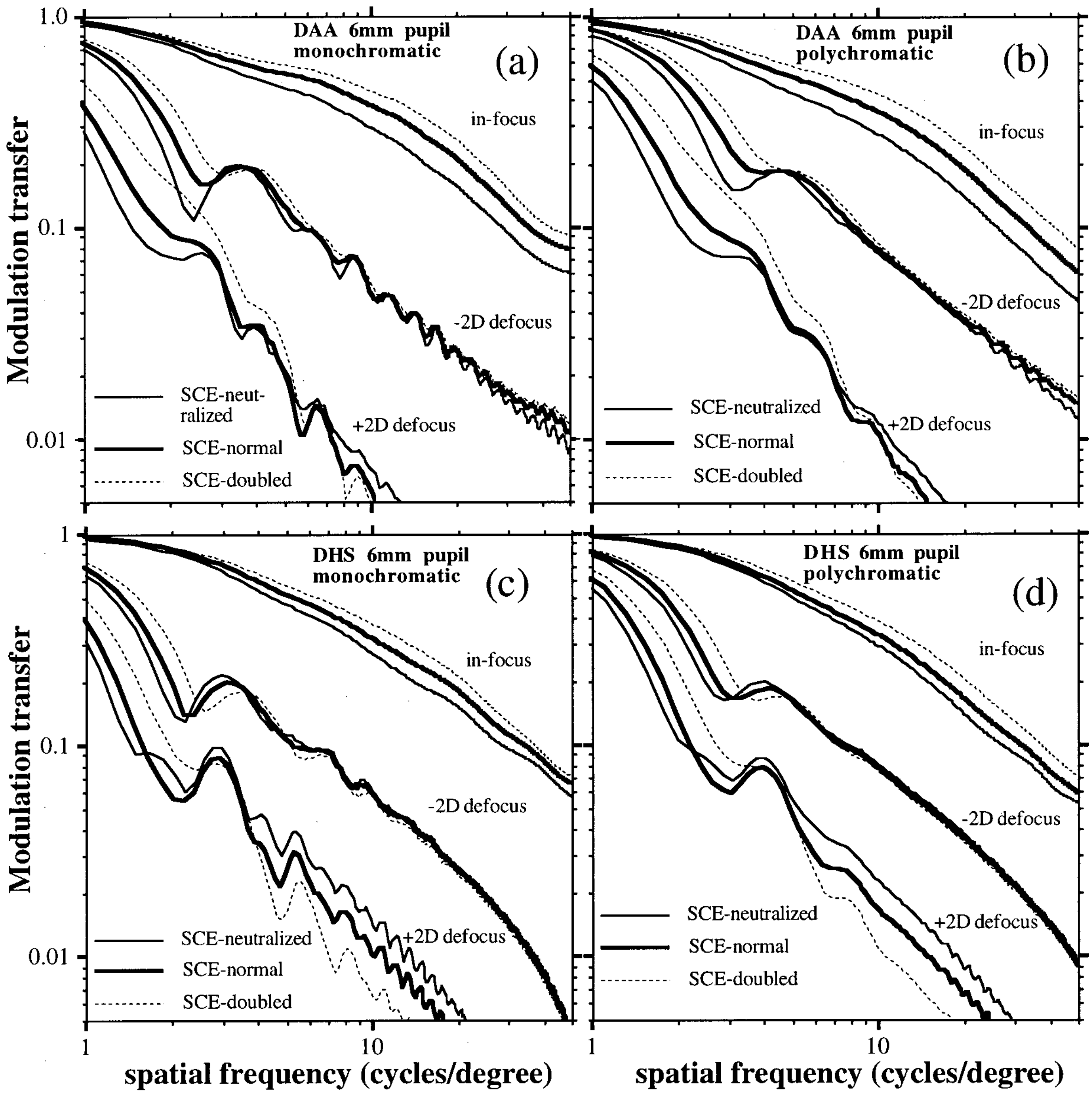

Fig. 5. MTFs for in-focus, −2 D defocus, and +2 D defocus and for the three SCE conditions. These are radial MTFs, obtained by averaging across all meridians. Medium solid curves indicate the SCE-neutralized condition, thick solid curves indicate the SCE-normal condition, and thin dashed curves indicate the SCE-doubled condition. Pupil diameter 6-mm. (a) DAA, monochromatic (550 nm), (b) DAA, polychromatic, (c) DHS, monochromatic (550 nm), (d) DHS, polychromatic.

data on the magnitude of the SCE at low luminances.[39,40] Crawford[39] measured the SCE at 5 deg eccentricity at a range of luminances in white light for two subjects. The parameter ρ varied from 0.012 to 0.12 mm^{-2} over the approximate luminance range of 0.01 to 10 cd m^{-2}, outside of which it was relatively constant. Assuming that these data hold for foveal vision also and combining them with the data of Reeves[31,32] indicates that a 6-mm pupil (1 cd m^{-2}) will occur with a slightly reduced ρ of 0.09–0.11 mm^{-2}, and a 7-mm pupil (0.03 cd m^{-2}) will occur with a much reduced ρ of 0.02–0.05 mm^{-2}. These results suggest that the importance of the SCE for visual acuity will be small below photopic levels.

A comparison of our visual acuity results can be made with other image quality measures. Figure 5 shows radial monochromatic and polychromatic MTFs for our two main subjects with 6-mm pupils under both monochromatic and polychromatic (equi-energy source) conditions. The maximum influence of altering the SCE is greater with defocus than for in-focus conditions, at least up to the defocused MTFs' "notches" at 2 or 3 cycles/degree. As for visual acuity, the SCE influence is greater for positive than for negative defocus. Note that although the SCE improves defocused MTFs at low spatial frequencies, it can worsen them at frequencies above that of the first notch, e.g., +2 D defocus for DHS [Fig. 5(c)]. Across the three defocus levels, the maximum influence of neutralizing the SCE is less than 0.25 lu and that of doubling the SCE is less than 0.2 lu.

Figure 6 shows monochromatic retinal reconstructions of letter E images for our two main subjects. These letters are near threshold for particular focus levels and have been scaled differently in the figure so that they all appear at the same size. Although the retinal images are distorted differently for the subjects, at any defocus level they show the same pattern and subjective magnitudes of change in quality caused by the SCE. For in-focus conditions, the different SCE conditions give fairly similar images. For −2 D defocus, the progression in improvement of image quality from the SCE-neutralized to the SCE-doubled condition is apparent but does not appear to make the letter much more recognizable. By contrast, the filtering for the +2 D defocus condition makes the letter much more recognizable. This fits well with the finding that manipulating the SCE has more influence at positive than at negative defocus.

Subject DAA's visual acuity appeared to be more influenced by manipulations of the SCE in near-monochromatic than in broadband light [compare Figs. 4(b) and 4(d)], despite the fact that the influence of the SCE on MTFs is similar for monochromatic and polychromatic conditions [compare Figs. 5(a) and 5(b) for DAA and compare Figs. 5(c) and 5(d) for DHS]. However, to determine the MTFs, we assumed that the SCE was the same at all wavelengths. However, the filters may not be equally effective at all wavelengths, either because of variable transmittance with wavelength or because the SCE becomes greater as wavelength both decreases and increases from ~550 nm.[41–45] Accordingly, additional SCE measurements were taken with the filters along the horizontal meridian, with blue (dominant wavelength 470 nm), green (575 nm) and red (620 nm) colors of the LED sources. For the SCE-neutralized condition, the mean ρ_x value of two runs was 0.02 for blue, green, and red.[20] For the SCE-doubled condition, the mean ρ_x values of two runs were 0.22 (blue), 0.21 (green), and 0.20 (red), with similar SCE peaks. These values indicate that the filters perform similarly over a range of wavelengths, and they do not explain DAA's small SCE-induced differences in visual acuity between near-monochromatic and broadband light.

Approximately 18 months after the SCE measures and SCE-modifying filters were made, and approximately 6 months after the visual acuity measurements were made, the SCE functions of subjects DAA and DHS were remeasured.[20] DHS showed no significant changes in his function, but DAA had a 0.4-mm temporal shift of the peak. This made only small changes to the efficiencies of DAA's filters and had little effect on recalculated MTFs and retinal image reconstructions. These comments are not applicable to PA and NS, for whom the visual acuity measurements were made within a month of determining their SCE functions.

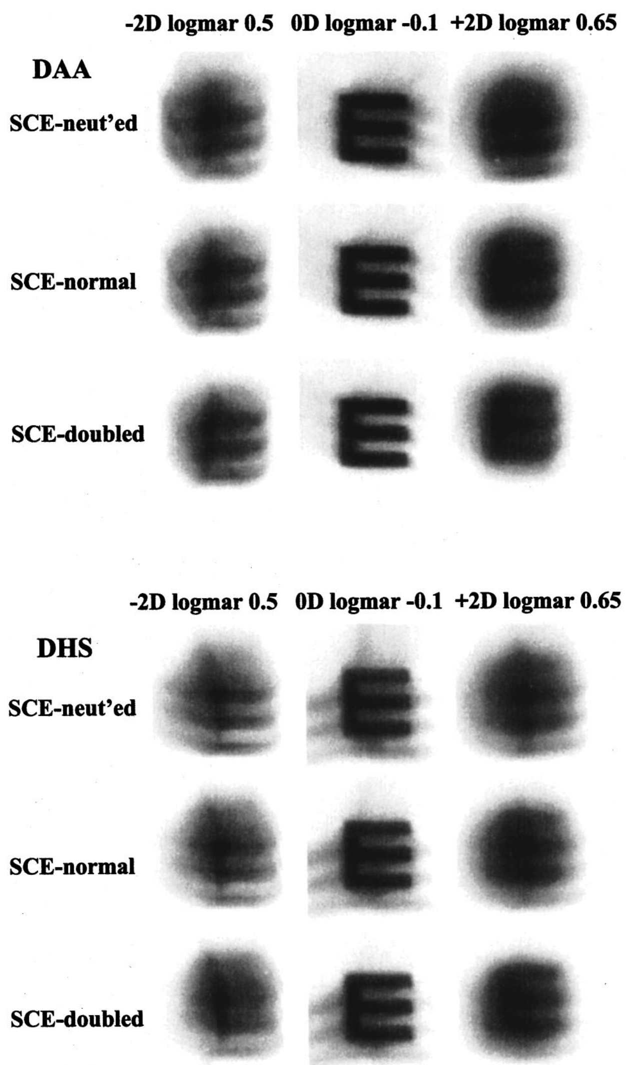

Fig. 6. Simulated high-contrast letter E retinal images for −2 D defocus (+0.5 logmar), in-focus (−0.1 logmar), and +2 D defocus (+0.65 logmar) combined with the three SCE conditions. Letter sizes <0.1 lu above threshold have been selected and the images scaled to be the same size. They have been cropped so that ~1/4 of the images are shown. The images show the view of an observer looking at the retina from the front; the subject would perceive the E's to be flipped vertically. Pupil diameter 6 mm, wavelength 550 nm. (a) DAA, (b) DHS.

B. Effect of Pupil Size on Visual Acuity

It is generally considered that the spatial performance of a defocused eye deteriorates markedly with increase in pupil size. However, subject DAA did not demonstrate much difference in visual acuity between pupil sizes for the SCE-normal condition. For example, from 4- to 7.6-mm pupils, he demonstrated a decrease in visual acuity of ~0.1 lu at both −2 D and +2 D defocus (SCE-normal condition) [Figs. 4(a)–4(c)]. Most of this small decrease for positive defocus can be attributed to the SCE; e.g., from 4- to 7.6-mm pupils with the SCE-neutralized condition, subject DAA demonstrated a decrease in visual acuity of ~0.3 lu.

We compared our findings of small difference between pupil sizes for the SCE-normal condition with values found in the literature. In Tucker and Charman's study,[7] across this pupil-size range subject WNC had deteriorations of ~0.1 lu and 0.15 lu at −2 D and +2 D defocus, respectively (their Fig. 5), while subject JT showed very asymmetrical results of <0.1 lu and ~0.25 lu at −2 D and +2 D defocus, respectively (their Fig. 4). The fitted results of Atchison *et al.*[46] for myopic defocus across this pupil-size range indicate a mean deterioration of 0.15 lu at +2 D defocus [their Fig. 6(b)]. Thus our result is not much different from these two studies. When a wide range of pupil sizes is considered, it becomes apparent that most of the changes in visual acuity with change in pupil size occur for pupil sizes less than 4 mm. This is also true for changes in depth of focus.[8,47–49]

C. Effect of Luminance on Visual Acuity (SCE Normal)

For high-contrast letters, our two main subjects showed 0.09-lu (DAA) and 0.14-lu (DHS) change in visual acuity per 1.0-lu change in luminance (Figs. 2 and 3). For low-contrast (15%) letters, the slopes were 0.14 and 0.16, with DAA showing an appreciable change in slope with change in contrast. If his results are restricted to the approximately 1.1-lu luminance range of DHS, his slope for low-contrast letters decreases until it is similar to the high-contrast slope. Johnson and Casson[50] found that visual acuity was more sensitive to luminance as letter contrast decreased, but the trend was very slight when 97%- and 12%-contrast letters were compared over a luminance range of 0.75 to 75 cd/m^2.

For subject DAA tested at high contrast, defocus did not affect the visual acuity/luminance slope (Fig. 2). When put on log–log plots as here, Sloan's results[51] had a slight increase in slope as positive defocus increased. The results of Simpson *et al.*[52] had a reduction in slope, but the change was small over a luminance range similar to that used here.

D. Effect of Letter Contrast on Visual Acuity (SCE Normal)

Our two main subjects showed different responses to letter contrast. In general, the differences in visual acuity between high- and low-contrast letters increased from −2 D defocus to +2 D defocus for both subjects. However, this was much more marked for DHS than for DAA [compare Figs. 4(b) and 4(e)], with DHS showing only ~0.05-lu difference for −2 D defocus. Johnson and Casson[50] found low-contrast acuity targets to be more affected than were high-contrast acuity targets by positive defocus out to +2 D, similar to our findings, but Ho and Bilton[53] found consistent differences in visual acuity between high- and low-contrast letters out to +2.50 D.

E. Asymmetry of Visual Acuity Results (SCE Normal)

For both main subjects, the decrease in visual acuity away from the in-focus condition was more marked for positive than for negative defocus, which was also evident in Tucker and Charman's two subjects[7] (their Figs. 4 and 5). This asymmetry was evident for all pupil sizes with high-contrast letters for DAA, with the slopes in the ratio of approx 1.3:1 [Figs. 4(a)–4(d)]. MTF results support this finding, as modulation transfer decreased more quickly with increase in spatial frequency for +2 D defocus than for −2 D defocus [Figs. 5(a) and 5(b)]. Subject DHS shows a pattern similar to that of DAA [Figs. 4(e), 5(c), and 5(d)]. This asymmetry is even more marked for the SCE-neutralized condition than for the SCE-normal condition.

5. CONCLUSION

We have shown that Stiles–Crawford apodization can influence visual acuity both in focus and out of focus. A considerable influence of nearly 0.3 log unit occurred for one subject's fully dilated pupil. The Stiles–Crawford apodization influence was a maximum of ~0.10 and 0.16 log unit in two subjects for a 6-mm pupil, a pupil size that we consider represents the upper limit of pupil sizes that are likely to occur naturally in the photopic luminance levels for which the SCE is at its maximum. The influence was minimal for a pupil size of 4 mm in one subject.

ACKNOWLEDGMENTS

This study was supported by a large Australian Research Council grant to David Atchison. Pablo Artal was supported by a Queensland University of Technology visiting fellowship. We thank Eddie Matejowsky for designing the electronics for the SCE and vernier alignment experiments, Stanley Klein for providing probit analysis software, and Peter Pejski for research assistance.

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