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# Young eyes for elderly people

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*Document Version*
Publisher's PDF, also known as Version of record

*Publication date:*
2009

Link to publication in University of Groningen/UMCG research database

*Citation for published version (APA):*
Gaalen, K. W. V. (2009). *Young eyes for elderly people: a clinical comparison of spherical and aspheric intraocular lenses*. s.n.

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# 2

# Relationship between contrast sensitivity and spherical aberration

## Comparison of 7 contrast sensitivity tests with natural and artificial pupils in healthy eyes

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*Journal of Cataract and Refractive Surgery 2009; 35:47-56*

## Abstract

### *Purpose*

To find a contrast sensitivity test that can be used clinically to evaluate interventions aimed at minimizing spherical aberration and determine the circumstances under which these tests should be performed.

### *Setting*

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### *Methods*

Contrast sensitivity tests were performed using 2 experimental designs. Design 1 was with a natural pupil under mesopic and photopic conditions. Design 2 was with a 5.0 mm artificial pupil after cycloplegia under photopic conditions only. Two computerized tests (vertical sine-modulated gratings [VSG] and Holladay circular sine-modulated patterns [HACSS]) and 5 chart tests (the Pelli Robson, acuity-measuring letter charts at low contrast [2.5% and 10%], VectorVision and edge contrast sensitivity) were used. Spherical aberration was assessed with a Hartmann-Shack wavefront analyzer.

### *Results*

Forty-nine healthy subjects aged 20 to 35 years (n=24) and 55 to 70 years (n=25) participated. Design 2 showed a significant relationship between contrast sensitivity and spherical aberration with the HACSS at 3 cycles per degree (cpd) ($P$ = .03) and 6 cpd ($P$ = .01) and with the VSG at 6 cpd ($P$ = .01). Design 1 yielded no significant relationships.

### *Conclusions*

Using an artificial pupil, a relationship between contrast sensitivity and spherical aberration was established with the VSG and HACSS tests but not with the chart tests. No test showed a relationship using natural pupils under either lighting condition. Chart tests are unsuitable for uncovering contrast sensitivity differences related to differences in spherical aberration, as typically found in healthy phakic eyes.

## Introduction

In recent years, cataract surgery has consisted of replacing the cataractous lens with a spherical intraocular lens (IOL). The young human lens, however, is anything but spherical and actually improves the optics of the eye by compensating for the spherical aberrations of the cornea. Hence, optical performance after cataract surgery can be less than perfect. In an attempt to further improve the optical performance of the pseudophakic eye, IOLs with optical properties more similar to those of the clear young human lens have been designed. Several studies[1-11] have found improved optical performance after the cataractous lens is replaced with a so-called aspherical IOL compared with the performance with a spherical IOL.

The results of cataract surgery with implantation of aspherical IOLs that aim to minimize spherical aberration can be evaluated using a Hartmann-Shack wavefront sensor and dynamic skiascopy. These techniques measure the optical aberrations of the eye precisely and objectively. The principles associated with these techniques were explained by Liang et al.[12] and Cervino et al.[13] The advantage of these methods is the objectivity, and the disadvantages are the high cost and that the apparatus does not measure visual performance directly.

In a clinical setting, contrast sensitivity testing with chart tests could be a simple and inexpensive method of directly evaluating visual performance after cataract surgery. Many contrast sensitivity chart tests are commercially available, including edge contrast sensitivity tests and letter contrast sensitivity tests, such as the Pelli-Robson[14] and the Mars,[15] which display single-size optotypes with decreasing contrast (Kooijman AC, et al. IOVS 1994; 35:ARVO Abstract 550). A different approach to contrast sensitivity testing with letter charts is the use of charts that present optotypes at a fixed low contrast with a range of sizes similar to that of visual acuity charts.[16]

Traditionally, contrast sensitivity is measured with gratings at a range of spatial frequencies.[17] These gratings can be generated by a computer and displayed on a monitor or presented with chart tests such as the VectorVision.[18] Computer-driven tests allow for continuous controllable contrast levels that enable precise assessment of the threshold at a wide range of spatial frequencies, which results in a complete contrast sensitivity function. The disadvantages of computer-driven tests are the long testing time and the relatively high cost of the equipment.

Recent studies that attempted to evaluate visual performance after the implantation of aspherical IOLs with contrast sensitivity measurements yielded conflicting results.[1-11,19-22] Therefore, we thought that a systematic inventory of the ability of contrast sensitivity tests to uncover the effects of differences in spherical aberration was long overdue. In this study, we selected 2 computerized tests and 5 chart tests. We assessed the ability of these tests to show a relationship between contrast sensitivity and spherical aberration, the latter measured with a wavefront sensor. We also explored the conditions under which contrast sensitivity measurements should be performed for this purpose.

## Subjects and methods

*Subjects and wavefront analysis*

The study adhered to the tenets of the Declaration of Helsinki and was approved by the Medical Ethical Committee of the University Medical Center Groningen. The study was registered in the ISRCTN register (trial ISCRTN66724598) and in the Dutch trial registers (trial 812).

Measurements were obtained from healthy subjects in 2 age groups (20 to 35 years and 55 to 70 years). Before inclusion in the study, subjects gave their written informed consent. Eyes with a refractive error of more than ±2.00 diopters (D) spherical equivalent were excluded, as were eyes with a cylindrical correction of more than 1.50 D or with a cylindrical correction that deviated more than 20 degrees from the horizontal or vertical axis. Only the dominant eye was tested. The best corrected visual acuity (BCVA) in that eye had to be at least 0.8 (20/25). Visual acuity after optimal subjective refraction was determined with an Early Treatment Diabetic Retinopathy Study (ETDRS) chart. No subjects had a known history of ocular pathology or surgery. To further document the absence of ocular pathology, corneal topography was performed (Orbscan II version 3.12, Bausch & Lomb, Inc.) and a dilated fundus photograph of the papillomacular region was taken and evaluated by an ophthalmologist.

Wavefront aberrations were measured with a wavefront analyzer (WASCA version 1.26.3, Asclepion Meditec) in standardized Optical Society of America values (micrometers).[23] The Zernike term $Z_4^0$ was used as a measure of the spherical aberration in the eye. Initially, wavefront aberrations were measured in 35 subjects in each age group to estimate the Gaussian spherical aberration distribution in that group. Next, subjects were selected from each age group to obtain roughly equal numbers of subjects in 4 subgroups (-2 SD to -1 SD; -1 SD to mean; mean to 1 SD; 1 SD to 2 SD). In other words, the aim was a uniform distribution around the mean spherical aberration. This resulted in 24 younger and 25 older subjects. This selection was performed to improve the observation of a potential effect of spherical aberration on contrast sensitivity. The spherical aberration was measured with a natural pupil (experimental design 1) and with an artificial pupil (experimental design 2). In experimental design 2, contrast sensitivity measurements started 30 minutes after cycloplegia and iridoplegia were obtained with cyclopentolate 1%.

*Contrast Sensitivity Tests*

Contrast sensitivity was tested using 2 computerized tests and 5 chart tests. Contrast sensitivity was measured at several spatial frequencies for both computerized tests and 1 chart test. The order of the tests was randomized. Tests were performed with best spectacle correction in a trial frame. Each test was performed at the recommended viewing distance, and the refractive correction of the subjects was corrected for that viewing distance at the beginning of each test.

The first computerized test, vertical sine-modulated gratings (VSG) (VSG 2/3 version 4.02, Cambridge Research Systems) generates vertical sine-modulated gratings (3 cycles per degree [cpd] and 6 cpd) on a cathode ray tube (Barco CCID7351B, Video & Communications n.v.) (Figure 1, *A*). This test was viewed at a distance of 2 m. The Von Békésy tracking method was used to assess the contrast threshold. In this method, the contrast changes continuously. First, it increases until the subject observes the pattern. On pressing a button, the contrast starts to decrease until the subject can no longer see the pattern. The contrast levels at which the gratings are reported as appearing and disappearing are recorded. The speed of change of contrast was set at 0.3 log/second. Six upper reversals and lower reversals were measured. The first, highest, and lowest values of both the upper and lower reversals were excluded. The remaining upper and lower reversals were averaged, resulting in the contrast threshold.[24] The grating pattern contrast is expressed in Michelson contrast:

$$\text{Michelson contrast} = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}} \qquad (1)$$

where $L_{\max}$ is the maximum luminance of the bright bars and $L_{\min}$ the minimum luminance of the dark bars. The order in which the spatial frequencies were tested was randomized. Contrast sensitivity was defined as the inverse of the measured contrast threshold.

The other computerized test was the Holladay automated contrast sensitivity testing system (HACSS) (M&S Technologies) (Figure 1, *B*). The circular sine-modulated patterns with spatial frequencies of 3 cpd and 6 cpd were used. The test begins with 50% contrast, starting at the highest spatial frequency. The subject indicates whether the displayed stimulus is a circular pattern or a blank disk. Throughout the test, several blank disks are shown at the same mean luminance level to check reliability. After each correct answer, the contrast of the stimulus decreases at steps of 0.3 log units. Near the threshold, contrast decreases by 0.1 log units. When an incorrect answer is given, contrast increases by 0.3 log units (after the second incorrect answer by 0.2 log units) and decreases by 0.1 log unit until the next incorrect response. The contrast threshold corresponds to the lowest contrast level at which the subject can correctly identify 2 of 3 circular patterns. The contrast sensitivity is based on Michelson contrast (equation 1). This test was performed at the recommended viewing distance of 4 m.

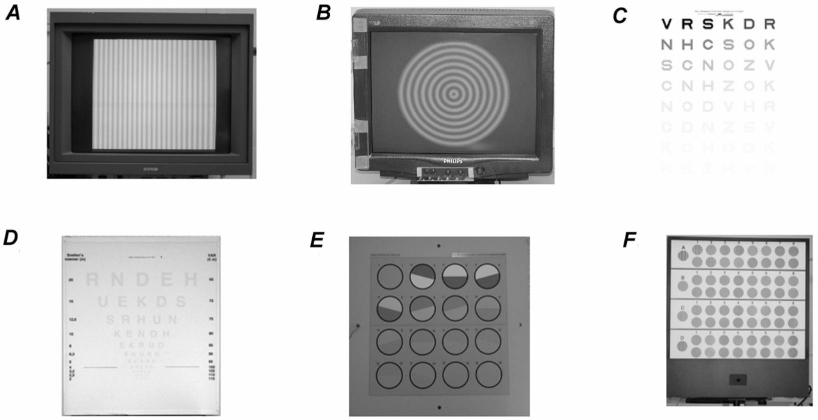

***Figure 1.*** *The contrast sensitivity tests used in this study.* ***A:*** *Vertical sine-modulated gratings,* ***B:*** *Holladay circular sine-modulated patterns,* ***C:*** *Pelli-Robson,* ***D:*** *Early Treatment Diabetic Retinopathy Study 2.5% and 10%,* ***E:*** *Groninger Edge Contrast chart (GECKO),* ***F:*** *VectorVision.*

The Pelli-Robson contrast sensitivity chart test (Clement Clarke International Ltd.) displays Sloan letters of constant size (Figure 1, *C*). The chart consists of 8 rows, each with 2 triplets. Contrast decreases from 1 triplet to the next in steps of 0.15 log units. Contrast sensitivity is expressed as the inverse of the Weber contrast:

$$\text{Weber contrast} = \frac{L_{\max} - L_{\min}}{L_{\max}} \tag{2}$$

where $L_{\max}$ is the luminance of the background and $L_{\min}$ the luminance of the letters. The test was performed at a viewing distance of 3 m, which corresponds to a spatial frequency of approximately 3 cpd.[25] The maximum log contrast sensitivity (logCS) that can be tested is 2.20. When a subject makes 2 mistakes within one triplet,[14] the test is terminated and then scored by letter.[26]

Two other chart contrast sensitivity tests were ETDRS-like optotype charts developed in the Laboratory of Experimental Ophthalmology, University of Groningen, with low contrast (2.5% and 10%) optotypes in Weber contrast (equation 2) (Figure 1, *D*). These charts measure resolution – the smallest optotype that can be seen – at a given fixed low contrast. The Visual Acuity Rate (VAR) values were used for statistical evaluation.[27,28] These tests were performed at a viewing distance of 1 m. When the subject makes the first mistake, the test is terminated and the last correct answer noted. Contrast sensitivity was scored by letter with a maximum VAR of 85 and a minimum VAR of 35.

Edge contrast sensitivity was measured using a test developed in Laboratory of Experimental Ophthalmology. This test, the Groningen Edge Contrast Chart (GECKO) (Figure 1, *E*) presents 16 circular targets (diameter 74.0 mm) divided into halves with different reflection values (Kooijman AC, et al. IOVS 1994; 35:ARVO Abstract 550). The contrast between the halves decreases in steps of 0.15 log units. The orientation of the separation line has a tilt +15 degrees, 0 degrees or -15 degrees in the vertical or the horizontal direction. The subject has to indicate the darkest half and the orientation of the separation line. When the subject makes the first mistake, the test is terminated and the last correct answer noted. The minimum contrast for this chart is 0.01 in Michelson contrast (equation 1), corresponding to a maximum logCS of 2.0. This test was performed at a viewing distance of 3 m.

The VectorVision contrast sensitivity chart test (VectorVision) (Figure 1, *F*) presents targets with sine-wave gratings at various spatial frequencies (3, 6, 12 and 18 cpd). These targets are presented on a double row of targets; 1 of the 2 vertically aligned targets is blank and the other, modulated. The subject has to indicate in which target the grating is present. When the subject makes a mistake, the testing of that particular spatial frequency is terminated and the last correct answer noted. The contrast, expressed in Michelson contrast (equation 1), decreases in steps of 0.15 log units. The minimum contrast for this chart corresponds to a logCS of 2.3. This test was performed at a viewing distance of 2.5 m.

### *Experimental designs*

#### *Experimental Design 1: Measurements with natural pupil*

In this experiment, subjects were asked to perform 2 computerized contrast sensitivity tests and 5 chart tests monocularly with their dominant eye. The order of the tests was randomized. Contrast sensitivity tests were performed at the optimum refractive state for their viewing distance under mesopic conditions (3 candelas [cd]/$m^2$) and photopic conditions (85 or 160 cd/$m^2$) without iridoplegia or cycloplegia. The mesopic condition was achieved by placing a neutral density filter in front of the eye. For the photopic conditions, the GECKO, VectorVision, VSG and HACSS were performed at a mean luminance of 85 cd/m² and the Pelli-Robson and low-contrast ETDRS at a luminance of 160 cd/m² of the white background. The luminance of the targets and the background was measured with a Minolta CS-100A chroma meter (Minolta Camera Co. Ltd.). A digital photo of the eye, with a ruler beneath the eye, was taken with both luminance conditions to measure the apparent pupil size (approximately 12% larger than the physical pupil size[29] as used in the WASCA software). Spherical aberration was measured and calculated for the individually measured photopic and mesopic physical pupil sizes using the WASCA software. Unless otherwise stated, all pupil sizes reported here refer to the apparent pupil size.

### *Experimental Design 2: Measurements with artificial pupil*

In this experiment, subjects were asked to perform 2 computerized tests, the VSG and the HACSS at 3 cpd and 6 cpd, and the Pelli-Robson test monocularly with the dominant eye. The remaining tests were discarded because of the results of experimental design 1 (see Results). The order of the tests was randomized. Cycloplegia and iridoplegia in the tested eye were obtained with 2 drops of cyclopentolate 1%. After 30 minutes, the pupil size was measured and the spherical aberration and contrast sensitivity measurements were begun. Contrast sensitivity tests were performed with optimum refraction for the viewing distance under photopic conditions (see experimental design 1). Measurements were performed with a 5.0 mm artificial pupil in the trial frame in front of the eye. The spherical aberration measurements were normalized to this 5.0 mm apparent pupil size and to the size of the maximally dilated pupil.

### *Statistical analysis*

The main outcome variable for all tests, except for the low-contrast ETDRS-like optotype charts, was the logCS value. The low-contrast ETDRS-like optotype chart results were expressed in VAR.[28] Statistical analyses were performed using the contrast sensitivity values and spherical aberration values of each subject separately. The nonparametric Mann-Whitney *U* test for independent samples was used to calculate the difference between the measured contrast sensitivity and spherical aberration values obtained from both age groups. The nonparametric Wilcoxon signed rank test for dependent samples was used to calculate the difference between the measured contrast sensitivity obtained under both lighting conditions. The relationship between the contrast sensitivity values and the absolute spherical aberration values (aiming at a linear relationship) was calculated with linear regression analysis. To confirm a normal distribution of the residuals, a nonparametric Kolmogorov-Smirnov *Z* test was performed. The means are presented with their standard deviation. A *P* value less than 0.05 was considered statistically significant.

## Results

Measurements were obtained from 49 healthy subjects in 2 age groups. The mean age in the 20 to 35 year group (younger group; n=24) was 25 years and in the 55 to 70 year group (older group; n=25), 60 years.

All 49 subjects participated in experimental design 1. In experimental design 2, 37 subjects agreed to participate; 17 were in the younger group (mean age 26 years) and 20, in the older group (mean age 62 years).

### *Pupil size and spherical aberration*

The mean BCVA was 107 VAR (range 103 to 113 VAR; -0.1 to -0.3 logMar; 20/16 to 20/10 Snellen) in the younger group and 107 VAR (range 100 to 113 VAR; 0.0 to -0.3 logMar; 20/20 to 20/10 Snellen) in the older group.

There was a statistically significant difference in mean natural pupil size between the mesopic condition and photopic condition in the younger group (4.78 ± 0.60 mm and 4.03 ± 0.64 mm, respectively; $P = .000$) and the older group (3.89 ± 0.53 mm and 3.21 ± 0.53 mm, respectively; $P = .000$). The difference between the younger and older groups was statistically significant under mesopic and photopic conditions (both $P = .000$). There was no difference in mean spherical aberration with a natural pupil between the younger group and older group under mesopic conditions (0.016 ± 0.072 µm and 0.012 ± 0.045 µm, respectively; $P = .650$) or under photopic conditions (0.002 ± 0.036 µm and -0.007 ± 0.035 µm respectively; $P = .749$). However, when spherical aberration was measured with an artificial pupil, the older group had a statistically significantly greater mean spherical aberration (0.054 ± 0.050 µm) than the younger group (0.024 ± 0.043 µm; $P = .045$). Figure 2 shows spherical aberration as a function of age measured during experimental design 2 after cycloplegia and iridoplegia with a 5.0 mm pupil.

Figure 3 shows the relationship between spherical aberration and pupil size with the natural pupil under mesopic and photopic conditions and after cycloplegia and iridoplegia. As expected, spherical aberration increased with increased pupil size. Spherical aberration values showed a large variation for pupils larger than 5.0 mm.

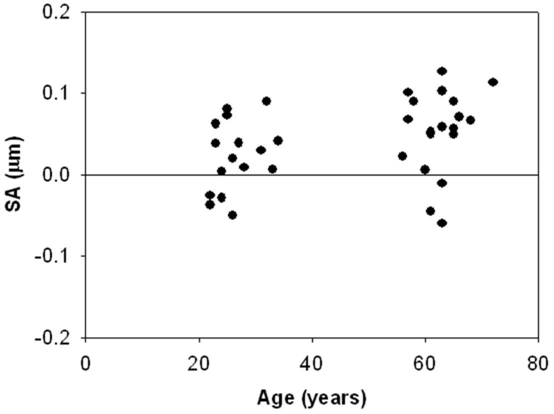

***Figure 2.*** *Spherical aberration as a function of age measured after cycloplegia and iridoplegia with a 5.0 mm artificial pupil (SA = spherical aberration).*

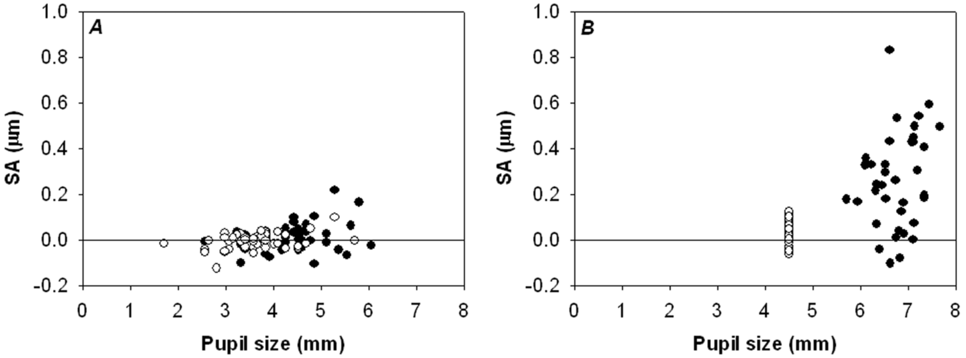

***Figure 3.*** *Spherical aberration as a function of pupil size.* ***A:*** *Natural pupil; the solid circles represent the mesopic condition and the open circles, the photopic condition.* ***B:*** *Artificial pupil; the solid circles represent spherical aberration measurements calculated for maximum dilated pupils and the open circles, spherical aberration calculations for an apparent 5.0 mm pupil (SA = spherical aberration).*

*Contrast sensitivity measurements*

There was a ceiling effect in the GECKO, in the 10% ETDRS-like optotype chart and the VectorVision test at 3 and 6 cpd because some subjects were able to read the most difficult targets in the charts (Table 1). In contrast, under mesopic conditions, a floor effect appeared in the 2.5% ETDRS-like optotype chart because some subjects were unable to perceive any optotypes (Table 1). Therefore, the results obtained using these tests were not evaluated further.

***Table 1.*** *Ceiling and Floor effects in contrast sensitivity chart tests.*

| | | Number of Subjects | | | |
|---|---|---|---|---|---|
| | | Mesopic | | Photopic | |
| Test | Effect* | Younger (n=24) | Older (n=25) | Younger (n=24) | Older (n=25) |
| 2.5% ETDRS-like optotype chart | Floor | 6 | 16 | 0 | 1 |
| 10% ETDRS-like optotype chart | Ceiling | 0 | 1 | 7 | 3 |
| GECKO | Ceiling | 11 | 4 | 16 | 11 |
| VectorVision at 3 cpd | Ceiling | 0 | 1 | 5 | 5 |
| VectorVision at 6 cpd | Ceiling | 3 | 1 | 9 | 3 |

*cpd = cycles per degree; ETDRS = Early Treatment Diabetic Retinopathy Study; GECKO = Groninger Edge Contrast Chart. * A ceiling effect means the test is too easy; all responses are correct. A floor effect means the test is too difficult; no response is assessed by the test*

Table 2 shows the mean contrast sensitivity values measured with a natural pupil at the optimum refractive state of the eye in the remaining tests under mesopic and photopic conditions. Due to technical problems, 3 subjects in both age groups did not perform the VSG test. Under mesopic conditions, the mean contrast sensitivity was statistically significantly lower than under photopic conditions in both age groups in all tests shown in Table 2 ($P \leq .05$). Furthermore, there was a statistically significant age-related decline in contrast sensitivity for HACSS measurements under both lighting conditions ($P \leq .05$).

Table 3 shows the mean contrast sensitivity values measured with an artificial pupil of 5.0 mm. The difference in contrast sensitivity between the younger group and older group was statistically significant for all of the tests except the Pelli-Robson.

***Table 2.*** *Mean logCS with a natural pupil measured with different contrast sensitivity tests by age group.*

| | Mean LogCS ± SD (Range) | | |
|---|---|---|---|
| Lighting and Test | Younger (n = 24) | Older (n = 25) | *P* Value |
| *Mesopic* | | | |
| HACSS at 3 cpd | 1.90 ± 0.17 (1.70-2.40) | 1.69 ± 0.13 (1.49-2.00) | .00 |
| HACSS at 6 cpd | 1.80 ± 0.16 (1.60-2.40) | 1.62 ± 0.17 (1.40-2.10) | .00 |
| VSG at 3 cpd [*] | 2.14 ± 0.20 (1.77-2.51) | 2.01 ± 0.25 (1.70-2.74) | .04 |
| VSG at 6 cpd [†] | 1.68 ± 0.24 (1.08-2.06) | 1.75 ± 0.27 (1.40-2.40) | .67 |
| Pelli-Robson | 1.49 ± 0.11 (1.35-1.65) | 1.39 ± 0.12 (1.20-1.55) | .01 |
| *Photopic* | | | |
| HACSS at 3 cpd | 1.94 ± 0.14 (1.75-2.40) | 1.81 ± 0.13 (1.50-2.00) | .00 |
| HACSS at 6 cpd | 1.96 ± 0.11 (1.80-2.40) | 1.87 ± 0.12 (1.60-2.10) | .02 |
| VSG at 3 cpd [*] | 2.35 ± 0.18 (1.90-2.76) | 2.42 ± 0.27 (1.72-3.03) | .32 |
| VSG at 6 cpd [†] | 2.10 ± 0.19 (1.67-2.35) | 2.20 ± 0.27 (1.72-2.72) | .28 |
| Pelli-Robson | 1.66 ± 0.06 (1.50-1.75) | 1.67 ± 0.07 (1.50-1.80) | .85 |

*cpd = cycles per degree; HACSS = Holladay circular sine-modulated patterns; LogCS = log contrast sensitivity; VSG = vertical sine-modulated gratings*

[*] *In the younger group, n = 21; in the older group, n = 22*

[†] *In the younger group, n = 17; in the older group, n = 20*

***Table 3.*** *Mean logCS with an artificial pupil measured under photopic conditions with different contrast sensitivity tests by age group.*

| | Mean LogCS ± SD (Range) | | |
|---|---|---|---|
| Test | Younger (n = 17) | Older (n = 20) | *P* Value |
| HACSS at 3 cpd | 1.76 ± 0.19 (1.45-2.10) | 1.61 ± 0.27 (1.20-2.40) | .02 |
| HACSS at 6 cpd | 1.93 ± 0.13 (1.70-2.15) | 1.73 ± 0.23 (1.35-2.40) | .00 |
| VSG at 3 cpd | 2.31 ± 0.13 (2.12-2.64) | 2.18 ± 0.26 (1.69-2.74) | .04 |
| VSG at 6 cpd | 2.23 ± 0.15 (1.89-2.49) | 2.01 ± 0.24 (1.62-2.51) | .00 |
| Pelli-Robson | 1.63 ± 0.09 (1.40-1.80) | 1.58 ± 0.11 (1.30-1.80) | .05 |

*cpd = cycles per degree; HACSS Holladay circular sine-modulated patterns; LogCS = log contrast sensitivity; VSG = vertical sine-modulated gratings*

### *Contrast sensitivity versus spherical aberration*

Figure 4 shows the relationship between contrast sensitivity assessed after cycloplegia and iridoplegia with a 5.0 mm artificial pupil and the absolute value of the corresponding spherical aberration (n = 37). A significant slope in the regression line was present in the results obtained with the HACSS at 3 cpd (*P* = .03) and at 6 cpd (*P* = .01) and with the VSG at 6 cpd (*P* = .01). With a natural pupil, there was no significant relationship between contrast sensitivity and spherical aberration for any test. The wavefront data used in the natural pupil situation were based on the actual pupil size of each individual subject. When these data were normalized to a 5.0 mm pupil in all subjects, no statistically significant relationships were found except the HACSS under mesopic conditions at 3 cpd ($r^2 = 0.12$; *P* = .033).

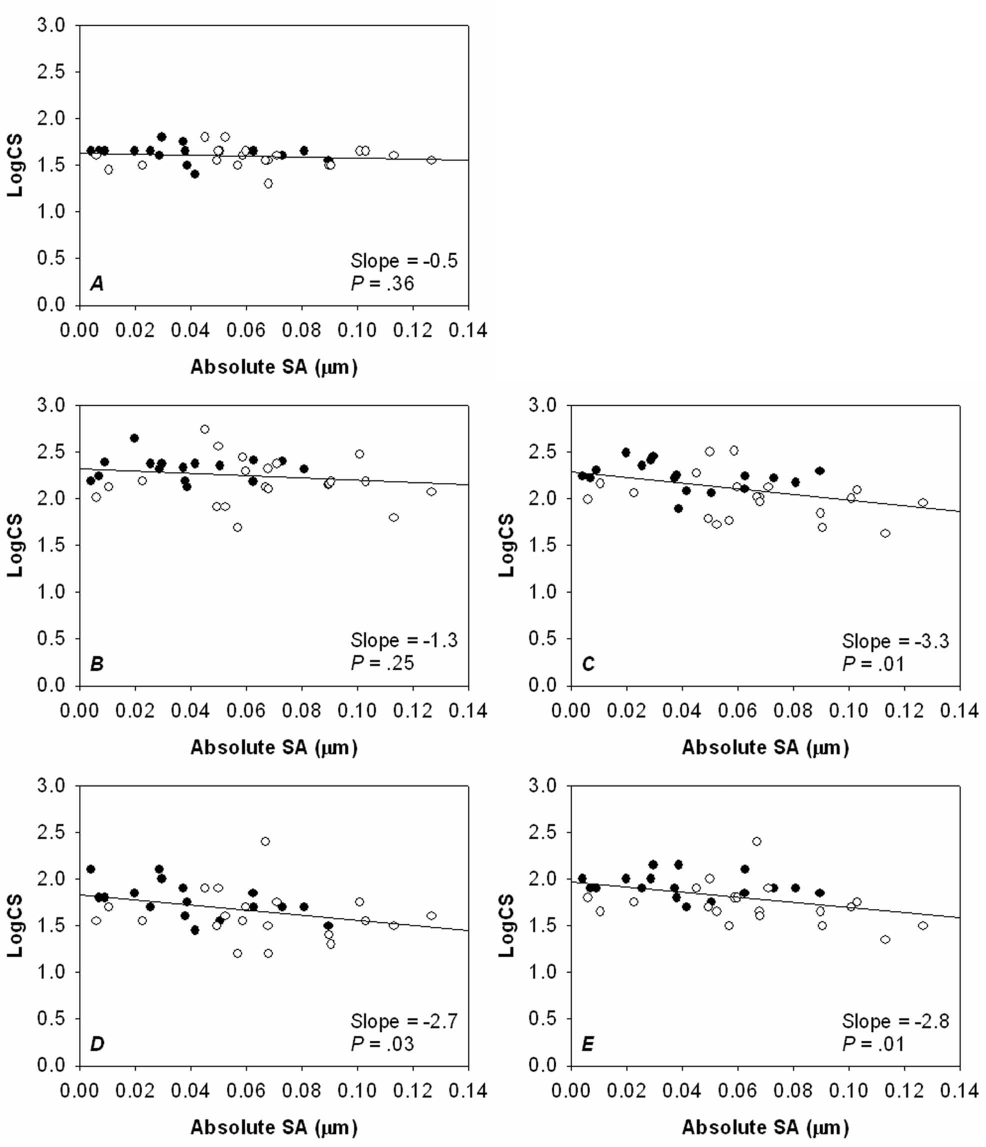

***Figure 4.*** *Log contrast sensitivity as a function of absolute spherical aberration measured with different contrast sensitivity tests with a 5.0 mm artificial pupil. Solid circles represent the young group, open circles the old group.* ***A:*** *Pelli-Robson.* ***B:*** *Vertical sine-modulated gratings at 3 cpd.* ***C:*** *Vertical sine-modulated gratings at 6 cpd.* ***D:*** *Holladay circular sine-modulated patterns at 3 cpd.* ***E:*** *Holladay circular sine-modulated patterns at 6 cpd (LogCS = log contrast sensitivity; SA = spherical aberration).*

## Discussion

In this study, we assessed the relationship between contrast sensitivity and spherical aberration using different contrast sensitivity tests with artificial and natural pupils. The experiments were performed in individuals who were emmetropic or near emmetropic and who were selected for their spherical aberration. Spherical aberration increases with age. With a 5.0 mm artificial pupil, a significant relationship between contrast sensitivity and spherical aberration was found for contrast sensitivity measurements performed with the HACSS at 3 and 6 cpd and the VSG at 6 cpd. No relationship was found between contrast sensitivity and spherical aberration when contrast sensitivity was measured with a natural pupil under mesopic or photopic conditions.

In the present study, only primary spherical aberration, represented by the Zernike term $Z_4^0$, was used. The $Z_4^0$ is reported to be the most important higher-order aberration term; other higher-order terms,[30,31] including secondary spherical aberration $Z_6^0$,[31] are much smaller. When replacing the absolute $Z_4^0$ by $\sqrt{((Z_4^0)^2 + (Z_6^0)^2)}$ in our data, the same relationships were found. Similarly, including coma did not improve the relationship between contrast sensitivity and the total amount of aberrations. For those reasons we confined our analyses to $Z_4^0$.

There are several possible explanations for the absence of a significant relationship in the natural pupil condition. Under the photopic condition, the pupils are small and the spherical aberration in eyes with a small pupil is nearly zero. This small spherical aberration barely affects retinal image quality, thus decreasing any possible relationship between spherical aberration and contrast sensitivity. Because a natural pupil was used, the pupil size, and thus the resulting retinal illumination, varied. Retinal illumination has a strong effect on the shape of the contrast sensitivity function,[32,33] especially at lower retinal illuminations. Thus, the variation in the retinal illumination in the test conditions might influence the assessed contrast sensitivity. Under photopic conditions, the luminance of the stimulus and its direct surroundings was between 85 cd/m$^2$ and 160 cd/m$^2$. The pupil diameters of the subjects varied between 2.0 mm and 6.7 mm. Hence, the resulting retinal illuminations ranged from $85 \text{ x } (2.0/2)^2 \text{ x } \pi = 267$ trolands to $160 \text{ x } (6.7/2)^2 \text{ x } \pi = 5638$ trolands. Under the mesopic condition, the luminance of the contrast tests was 3 cd/m$^2$ and the measured pupil diameter varied between 3.0 and 7.0 mm. The resulting retinal illuminations ranged from $3 \text{ x } (3/2)^2 \text{ x } \pi = 21$ trolands to $3 \text{ x } (7.1/2)^2 \text{ x } \pi = 119$ trolands. Van Nes et al.[32] and Van Nes[33] found that contrast sensitivity increases monotonically from 0.0009 trolands to 90 trolands and stabilizes at higher retinal illuminance; the peak of the contrast sensitivity function increased by 0.2 log units between 9 trolands and 90 trolands. This implies that the influence on contrast sensitivity of the variation in retinal illumination can be ignored under photopic conditions but not under mesopic conditions. Under mesopic conditions, the beneficial effect of a small pupil on contrast sensitivity through lowering the spherical aberration is counteracted by the adverse effect of the lower retinal illumination. In addition, the variation in retinal illumination under mesopic conditions and the resulting variation in contrast sensitivity might add too much variation to produce any statistically significant effect of spherical aberration on contrast sensitivity. Thus, with a natural pupil, the small spherical aberration value for small pupils could explain the absence of a clear relationship between spherical aberration and contrast sensitivity under photopic conditions. The dependence of contrast sensitivity on retinal illumination could explain this absence under mesopic conditions.

By also measuring contrast sensitivity with an artificial pupil in front of a dilated pupil, we were able to combine a larger pupil size and thus, in general, a larger spherical aberration with a high and constant retinal illumination. This condition eliminates the influence of retinal illumination on contrast sensitivity, increasing the influence of spherical aberration on contrast sensitivity variation. In this study a significant relationship between contrast sensitivity and spherical aberration was measured in 2 of the 3 contrast sensitivity tests.

Another phenomenon that could reduce the influence of spherical aberration on contrast sensitivity is the Stiles-Crawford effect, which describes the directional sensitivity of the retina as a difference in sensitivity between light that enters the eye through the center of the pupil as opposed to through the periphery.[34] Peripheral rays, whose refraction is the most influenced by spherical aberration, are less effective in stimulating the retina than the central rays. The spherical aberration causes a widened distribution of peripheral light rays around the ideal image of a point source at the retina, but its influence on the perceived image is decreased by the Stiles-Crawford effect. Spherical aberration, measured in this study using a wavefront analyzer, is not influenced by the Stiles-Crawford effect. Olsen[35] found that the Stiles-Crawford effect reduced the distance between the effective focus and paraxial focus in pupils larger than 4.0 mm, thereby minimizing the effect of spherical aberration, which could explain the moderate relationship between contrast sensitivity and spherical aberration found in the present study.

In this study, both age groups were plotted together in Figure 4 to establish a relationship between contrast sensitivity and spherical aberration. Therefore, age-related changes in contrast sensitivity due to causes other than a change in spherical aberration could be a confounder in this analysis. Both optical factors[36-39] and neural changes[40-44] have been reported to contribute to age-related changes in contrast sensitivity. Controversy exists regarding the primary cause of this loss in visual performance. Age-related measurements have been performed in young, middle-aged and older subjects. No significant difference between the young and the middle-aged groups was found; however, the older subjects had significantly lower contrast sensitivity.[36,40,45-47] Several studies have compared the visual performance of phakic and pseudophakic eyes. The visual performance of subjects with a spherical IOL was comparable to that of age-related phakic subjects but worse than that of younger subjects.[48,49] Furthermore, implantation of an aspherical IOL resulted in a higher visual performance than implantation of a spherical IOL.[1-11] These findings suggest that the lens is the primary cause of loss in visual performance with age. In the present study, we were unable to distinguish optical from neural factors. However, this does not explain the absence of a relationship between contrast sensitivity and spherical aberration in our study.

To conclude, in this study the influence of spherical aberration on contrast sensitivity in phakic subjects with clear lenses could only be established with computer tests and by using cycloplegia and an artificial pupil. Chart contrast sensitivity tests are not suitable. Unfortunately, computer tests are difficult to perform in a clinical setting due to the long testing times and high cost. Therefore, contrast sensitivity testing is not an easy-to-apply tool for the assessment of spherical aberration and the changes in it.

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