

Impact of scattering and spherical aberration in contrast sensitivity

Guillermo M. Pérez

Laboratorio de Optica, Departamento de Física,
Universidad de Murcia, Campus de Espinardo,
Edificio CiOyN, Murcia, Spain



Silvestre Manzanera

Laboratorio de Optica, Departamento de Física,
Universidad de Murcia, Campus de Espinardo,
Edificio CiOyN, Murcia, Spain



Pablo Artal

Laboratorio de Optica, Departamento de Física,
Universidad de Murcia, Campus de Espinardo,
Edificio CiOyN, Murcia, Spain



We investigated the impact in spatial visual performance of the combined presence of different amounts of spherical aberration and intraocular scattering in the eye. In a group of subjects, contrast sensitivity at 6 cycles per degree was measured when viewing through holographic diffusers to produce different levels of scattering and with their spherical aberration simultaneously controlled using an adaptive-optics visual simulator. For elevated levels of scattering, the addition of small amounts of spherical aberration either does not decrease, or even may slightly increase, contrast sensitivity under some conditions. This seems to be due to an optical effect also demonstrated in an artificial eye. Although the visual effect is quite small, this finding could suggest a balancing mechanism where larger spherical aberration could keep relatively stable the retinal image quality under the presence of elevated scattering. This is actually the situation in older eyes with both spherical aberration and intraocular scatter being higher than in young eyes.

Keywords: optical aberrations, spherical aberration, intraocular scattering, visual performance, adaptive optics

Citation: Pérez, G. M., Manzanera, S., & Artal, P. (2009). Impact of scattering and spherical aberration in contrast sensitivity. *Journal of Vision*, 9(3):19, 1–10, <http://journalofvision.org/9/3/19/>, doi:10.1167/9.3.19.

Introduction

The study of the eye's higher order aberrations (Artal, Guirao, Berrio, & Williams, 2001; Liang & Williams, 1997; Artal, Benito, & Tabernero, 2006) and their impact on spatial vision has been one of the most important topics in Visual Optics during the recent years.

The ocular aberrations tend to increase during normal aging degrading the quality of the retinal images (Artal, Ferro, Miranda, & Navarro, 1993; McLellan, Marcos, & Burns, 2001). The increase of the ocular aberrations with age has been explained as the result of the progressive loss of the compensatory effect established between the aberrations of the cornea and the crystalline lens (Artal, Berrio, Guirao, & Piers, 2002). This disruption on the aberrations compensation is produced not by changes in the cornea (Guirao, Redondo, & Artal, 2000) but by the progressive morphological changes occurring in the crystalline lens with age. There are significant changes in the lens' radii of curvatures (Brown, 1974), thickness (Koretz, Handelman, & Brown, 1984), and refractive index distribution (Hemenger, Garner, & Ooi, 1995; Smith, Atchison, & Pierscionek, 1992). The optical

consequence of these structural changes in the lens is the increase of the aberrations for the whole eye. In the particular case of the spherical aberration (SA), there is a tendency to increase for the whole eye toward positive values. While the SA of the cornea remains constant, aging changes the SA of the lens from negative to positive values, leading to an overall increase in the eye's SA. This situation can even be accelerated by early age-related pre-cataract processes, which further changes toward positive values the SA of the lens (Rocha et al., 2007).

The relationship between optical aberrations and vision has been also widely studied (Applegate, Marsack, & Thibos, 2006; Marsack, Thibos, & Applegate, 2004; Villegas, Alcón, & Artal, 2008). Although the presence of ocular aberrations decreases visual performance, it has been recently shown that young eyes with different amounts of normal aberrations have similar visual acuity (Villegas et al., 2008). In addition, some of the subjects in that study with the highest visual acuity had normal amounts of aberrations.

The use of adaptive optics to either correct or manipulate the eye's aberration when performing visual tests provided a powerful tool to better understand how the optical quality affects vision. The complete correction of high-order aberrations significantly improved visual

performance (Liang & Williams, 1997; Yoon & Williams, 2002). The correction of some particular aberration terms, in particular spherical aberration, also produced an improvement in both visual acuity and contrast sensitivity (Piers, Fernandez, Manzanera, Norrby, & Artal, 2004; Piers, Manzanera, Prieto, Gorceix, & Artal, 2007). However, the visual system seems to be adapted to the aberrations (Artal et al., 2004). This may cause a lower than expected impact in vision after correcting normal aberrations.

Monochromatic aberrations may also affect some other aspects of vision: tend to increase depth of focus (Marcos, Moreno, & Navarro, 1999), may reduce the detrimental effect of the longitudinal chromatic aberrations in white light (McLellan, Marcos, Prieto, & Burns, 2002), or they can contribute to some extent to the mechanism of the accommodation (Fernández & Artal, 2005). These effects suggest that, depending on the visual conditions, the presence of normal aberrations may actually improve visual performance for some specific visual tasks.

Intraocular scatter is another important optical factor affecting visual performance. Many studies showed a progressive increase of intraocular scattering with age. This tendency has been clearly demonstrated by using both subjective (IJspeert, de Waard, van den Berg, & de Jong, 1990) and objective techniques (Westheimer & Liang, 1994). The detrimental effect of scatter on visual quality, and specifically on contrast sensitivity (CS), has also been shown by different studies (Hemenger, 1984; Westheimer & Liang, 1995). Intraocular scattering imposes a different and specific visual condition on the aged eyes, and therefore, this could affect the role played by the presence of aberrations. The simultaneous presence of both scatter and aberrations may affect differently retinal image and vision. Since these two optical factors change through the life span, it could be argued that the relative changes could be tuned to optimize performance.

In this context, we first designed an experiment to investigate the impact of the simultaneous presence of scattering and spherical aberration in the image quality of an artificial eye. Next, we performed what is to our knowledge the first experiment to test spatial vision in subjects for controlled conditions of induced SA and scatter. We used an adaptive optics visual simulator combined with appropriate diffusers to accurately control both SA and scatter.

Methods

Measuring image contrast in an artificial eye

We built an artificial eye equipped with a variable diffuser to introduce scatter and aspheric plates to induce SA. These two components were placed in front of a CCD camera. Defocus was controlled by the camera objective and the aperture was set to 8 mm (Figure 1).

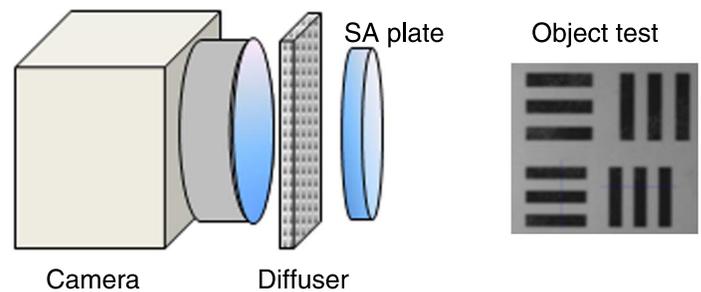


Figure 1. Schematic of the artificial eye setup.

Images of an object test were recorded by the CCD camera for different combinations of defocus, SA, and scatter. The object was a section of the USAF 1951 test placed at 40 cm from the camera, i.e., with the main spatial frequency of the bar pattern being approximately 2.5 cycles/degree. The measured contrast in the recorded images was used to quantify the relative degradation induced by different combinations of SA and scatter (Pérez & Artal, 2006).

The variable diffuser was a sheet of Polymer Dispersed Liquid Crystal (PDLC) inserted between two windows plates (Körner, Scheller, Beck, & Fricke, 1994). The amount of induced scatter was controlled by the voltage applied, which modifies the alignment of the liquid crystal molecules. A low voltage produces a large amount of scatter, while high voltages produce low scatter. We measured the contrast of the images recorded for different combinations. The values of the selected SA were between -0.3 and $+0.3 \mu\text{m}$ and the amount of defocus ranged between -0.4 and $0.4D$.

To establish the relative impact of SA and defocus in image contrast for different amount of scatter, we calculated a parameter, the relative contrast difference (RCD), given by

$$\text{RCD} = \frac{\text{Contrast}_{(SA, D)} - \text{Contrast}_{(SA=0, D=0)}}{\text{Contrast}_{(SA, D)}}, \quad (1)$$

with *Contrast* being the values of contrast in the images obtained with a given value of SA and defocus (SA, *D*) or at best focus and without SA (SA = 0, *D* = 0).

Visual testing through spherical aberration and scatter

Experimental system: Adaptive optics visual simulator and scattering

We used a modified adaptive optics instrument to control and manipulate both aberrations and scattering while visual testing was performed. Figure 2 shows a schematic representation of the setup. The instrument is similar to those previously described (Fernández, Manzanera, Piers, & Artal, 2002; Piers et al., 2004, 2007) but with the

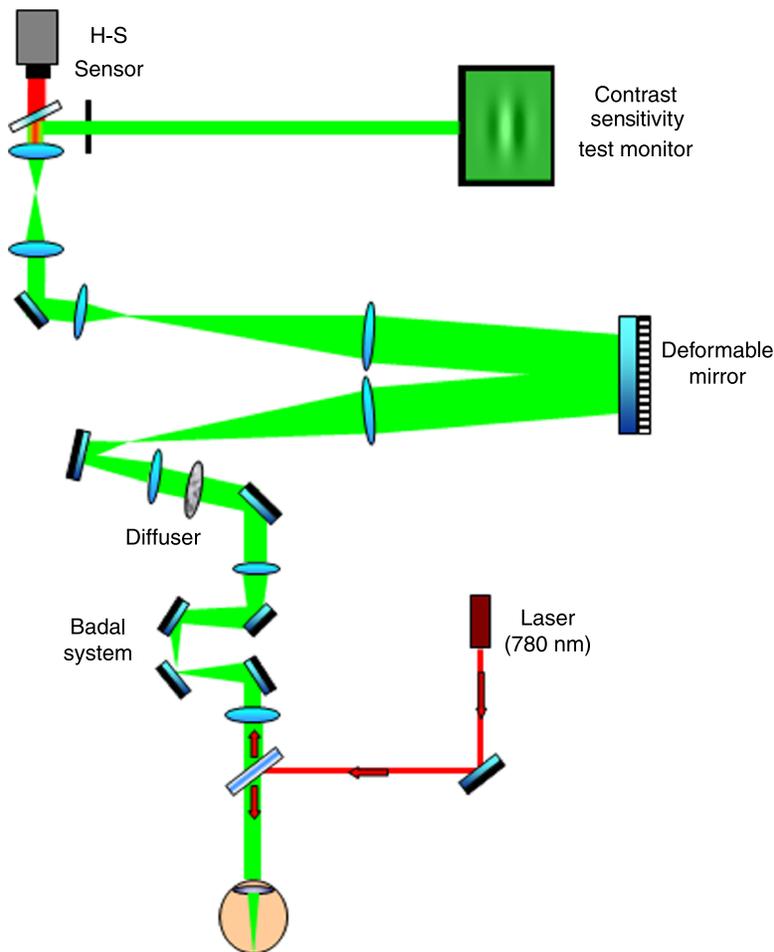


Figure 2. Schematic representation of the experimental system. See text for additional details.

incorporation of a holographic diffuser in the visual path to introduce scatter. A near-infrared (780 nm) diode laser illuminates the eye after reflection in a beam splitter placed in front of the eye. The eye pupil is imaged onto both the deformable mirror and the wavefront sensor by means of telescopic relay lenses. The deformable mirror is a Xinetics 97-actuator and the wavefront sensor is a Hartmann–Shack (H–S) type (Prieto, Vargas-Martín, Goelz, & Artal, 2000). The sensor measures the ocular aberrations and those induced by the mirror, and both working in closed-loop set the target wave aberration. This wave aberration is expressed in terms of Zernike polynomial modes, and the system is able to reach a final wave aberration composed of any possible combination of values of these modes. The overall defocus is set by using a Badal-type optometer (Atchison, Bradley, Thibos, & Smith, 1995). In this experiment, the adaptive optics system has been used to modify the SA term (Z_4^0), either leaving unchanged or correcting the rest of the aberration modes. To achieve this, initially the system measures the eye's aberrations and set these values as the target aberration, except for the SA whose value is previously stated as desired. When all the other aberrations want to be corrected, the target values are set to zero. Pupil size

and eye location were monitored by an auxiliary video camera during the complete experiment. Proper alignment of the eye's pupil with respect to the wavefront sensor and the deformable mirror was assured by using a bite bar.

Subjects

The measurements were carried out in a group of 4 young subjects (mean age: 28.2 ± 3.6 years). They were normal subjects according to a standard ophthalmological exam. All measurements were obtained with paralyzed accommodation and the pupil dilated after instilling two drops of tropicamide 1%. The study followed the tenets of the Declaration of Helsinki, and signed informed consent was obtained from the subjects after the nature and all possible consequences of the study had been explained.

Protocol of the visual performance measurements

To perform the visual testing through the modified aberrations and scatter, an additional path was incorporated (see Figure 2), composed of a distant CRT monitor, where sinusoidal gratings were displayed, a cold mirror that allows the subject to see the test through the optical

setup, and a circular aperture, conjugated with the eye pupil plane acting as artificial pupil.

In addition, scatter was induced by means of holographic diffusers (Physical Optics, Torrance, CA) placed in the system conjugated with the eye pupil. These diffusers have a low contribution to backscatter (Wadle & Lakes, 1995), and therefore, they hardly affect the luminance of the test. The amount of scattering generated by these diffusers is characterized by the value of the angular width at half of the maximum of a collimated light beam passing through the diffuser. The values of the two diffusers used here were 0.5° (diffuser 1) and 1° (diffuser 2).

We induced three values of the SA: 0, +0.1, and +0.15 μm for a pupil diameter of 4.8 mm. These three values of SA were combined with two different aberration configurations: when the rest of the aberrations were not modified (we called this “natural” case) and when all the other aberrations were corrected (“corrected” case).

We measured contrast sensitivity (CS) for 6 cycles/degree, using a forced-choice procedure, for the series of different combinations of aberrations: six cases (3 values of SA for both natural and corrected aberrations); and scattering: three cases (no diffuser and diffusers 1 and 2).

During the measurements, each optical condition was selected in a random temporal sequence to avoid undesired learning or adaptation processes. When the required value of SA was set, subjects adjusted their best focus position with the motorized Badal optometer. For each condition, CS was measured for a fixed artificial pupil of 4.8 mm in pseudo-monochromatic green light. The

spectrum of the CRT green phosphor has a peak around 532 nm with an approximate width at half height of 70 nm (Cowan, 1995). CS was estimated from the measured contrast threshold by

$$CS = \frac{1}{\log_{10}(\text{Contrast Threshold})}. \quad (2)$$

To have a quantitative comparison of CS for different scatter levels with and without SA, we calculated a parameter, the Relative Contrast Sensitivity Difference (RCSD), given by

$$RCSD = \frac{CS_{SA} - CS_{SA=0}}{CS_{(SA=0)}}, \quad (3)$$

where CS_{SA} is the contrast sensitivity for a specific SA value and $CS_{SA=0}$ is the contrast sensitivity for the SA-free case.

Results

Contrast changes in the artificial eye

Figure 3 shows the results of the relative contrast difference (RCD parameter) for some of the tested combinations in the artificial eye. Without scattering, i.e., with no diffuser (top panel), RCD is negative indicating the

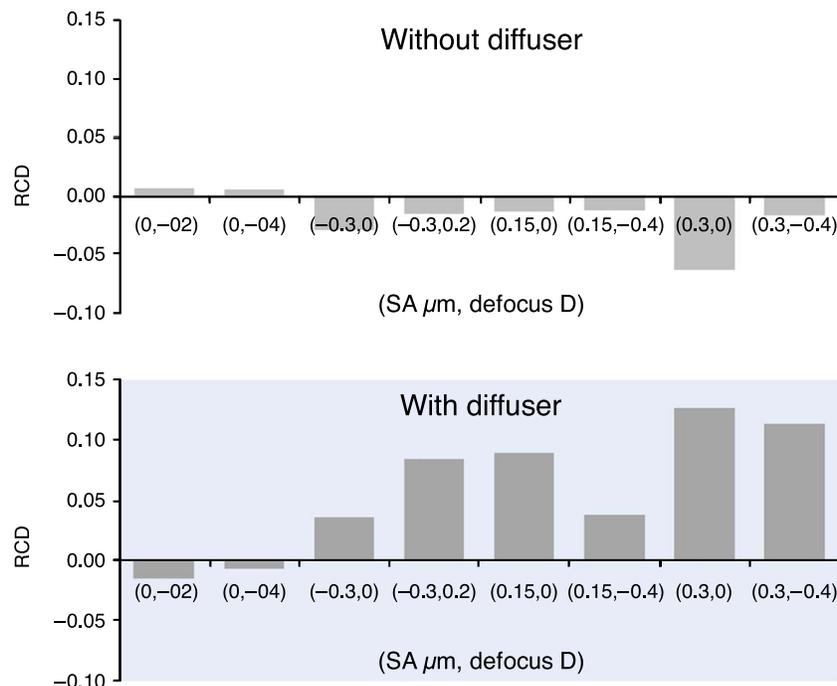


Figure 3. RCD parameter for different combinations of SA and defocus measured in an artificial eye without (top panel) and with (bottom panel) scatter induced. The notation for each configuration represents the magnitude of the SA in microns followed by the amount of defocus in diopters.

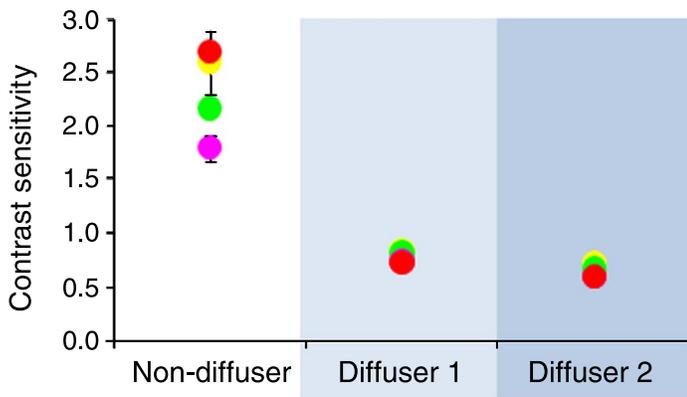


Figure 4. Contrast sensitivity (CS) for the four subjects with their normal aberrations for the three scattering conditions: Non-diffuser (scattering-free case), diffusers 1 (0.5°) and 2 (1°).

expected situation of a reduction of contrast in the images when SA and defocus were added. For some cases, small positive values are due to a possible balance between the added SA and that present in the camera objective. However, in the case of induced scattering, i.e., with diffuser (bottom panel), values of RCD tend to be positive for different combinations of SA and defocus, indicating that by adding SA and defocus the contrast in the images actually improved in the presence of scatter.

Contrast sensitivity with SA and scattering

Figure 4 shows the results of CS for every subject with their normal aberrations when viewing the test through each diffuser or without any diffuser (scatter-free case). It can be clearly noted the well-known impact of scatter to reduce performance around 4 times in average.

For the scatter-free case (i.e., without diffuser), CS was always higher when SA aberration was corrected. This corresponds to a negative value of the RCD parameter,

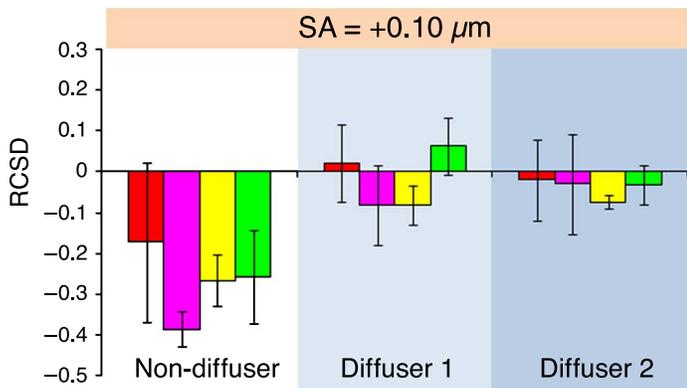


Figure 5. RCD for all the subjects with SA = $0.1 \mu\text{m}$ in “natural” configuration. Each color bar corresponds to one particular subject. Error bars are the *SD* obtained from the CS measurements.

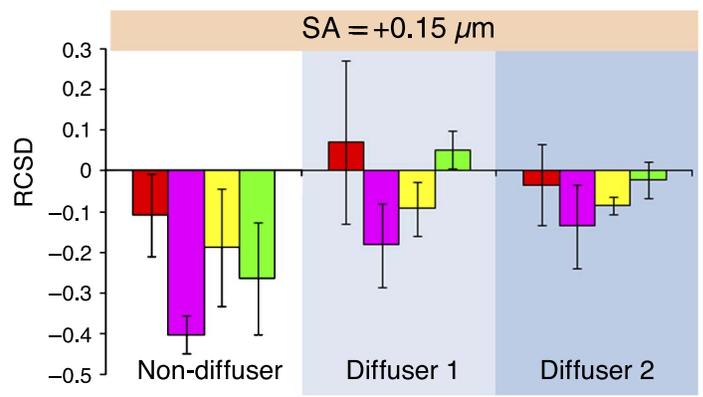


Figure 6. RCD for all the subjects with SA = $0.15 \mu\text{m}$ in “natural” configuration. Each color bar corresponds to one subject. Error bars are the *SD* obtained from the CS measurements.

indicating that, as expected, the addition of SA reduces contrast sensitivity. If this would also be the case for the configurations with induced scatter, this parameter should always be negative.

Figures 5 and 6 show RCD values obtained for SA of $0.1 \mu\text{m}$ and $0.15 \mu\text{m}$, respectively, for the four subjects evaluated, when one of the diffusers is set in the system, as compared with the scatter-free configuration, i.e., without diffuser. These results show that, without diffuser, the relative contrast sensitivity (RCD) values are always negative. However, with the presence of scatter, RCD values tend to be around zero or even slightly positive. Therefore, with scatter, contrast sensitivity is not reduced when some amount of SA is added.

Since SA interacts with the other aberrations, we also measured CS for the combined effect of scatter and SA when all the other aberrations were cancelled (“corrected” case). Figure 7 shows for one subject the effect of adding the same amount of SA on the normal aberration (“natural”) or the aberration-free (“corrected”) configurations.

Figures 8 and 9 show the comparison of the values of RCD with “natural” and “corrected” configuration for two of the subjects. For this comparison, we selected the two subjects who did not reach positive values of RCD with the “natural” configuration under the presence of scatter. We wanted to check whether the lack of improvement in their contrast sensitivity by adding the SA was due to the interaction between SA and their other ocular aberrations. RCD values were less negative in the corrected cases. This indicated that when all the other aberrations are corrected, adding SA in the presence of scatter produces a slightly higher beneficial effect.

Discussion

We first evaluated in an artificial eye how image contrast is affected by the addition of small amounts of

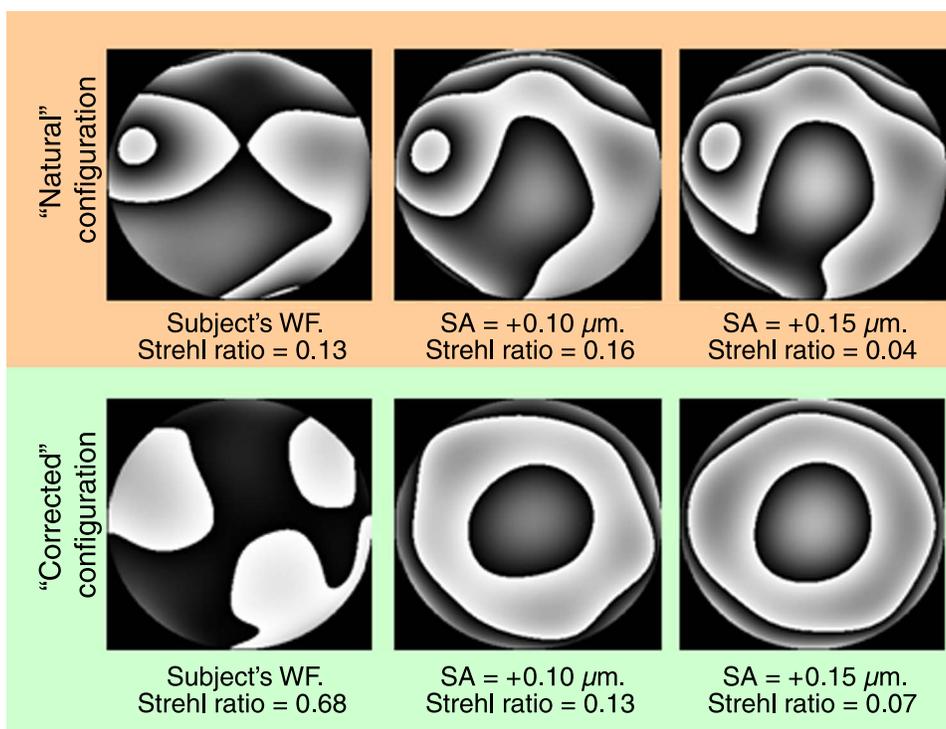


Figure 7. Wavefront aberrations in one of the subjects for the different conditions (see text for details).

SA in the presence of scatter. While without scatter adding small amounts of SA reduces contrast, with scatter the contrast of the image is slightly improved by the addition of adequate amounts of SA in combination with defocus. This may indicate that the combined presence of scatter and SA could alleviate their separate deleterious effect in image contrast.

To better understand these results, we have also performed a computer simulation of the image forming process by adding random phase plates to the generalized pupil function to simulate the effect of scattering (Navarro, 1985). We calculated the contrast in the images of the objects for different ascending level of induced

scattering, generated by a collection of random phase plates. The PSF corresponding to every case was computed and the convolution of this PSF with an object test provided the image of the object test viewed through the corresponding level of scatter (SC0 to SC4 in Figure 10).

We replicated in the simulation a range of conditions similar to those in the experiment of the artificial eye, with controlled amounts of SA and defocus. Figure 11 shows some of the results from these simulations. The relative contrast difference (RCD) of Equation 1 was computed for every combination of defocus and SA for increasing levels of scatter (from SC1 to SC4). The red areas in the figures show the combinations of SA and defocus, which produce

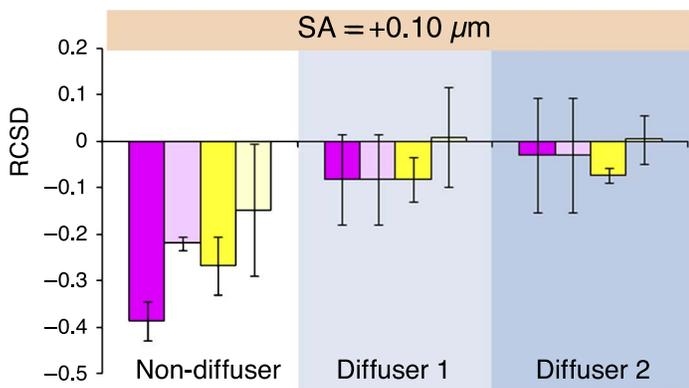


Figure 8. RCD for two subjects with SA = 0.1 μm in “natural” (darker color bars) and “corrected” configurations (lighter color bars). Each color represents the results for one subject.

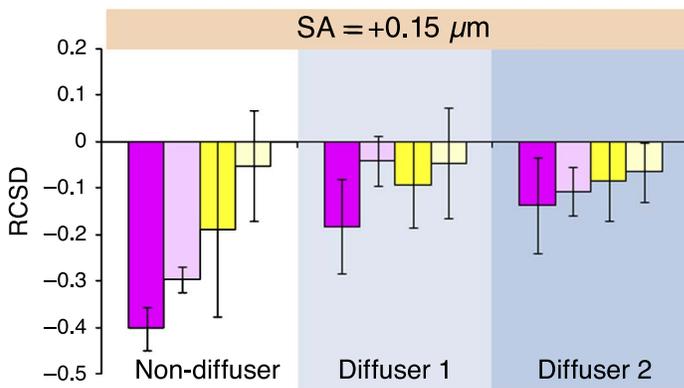


Figure 9. RCD for two subjects with SA = 0.15 μm in “natural” (darker color bars) and “corrected” configurations (lighter color bars). Each color represents the results for one subject.

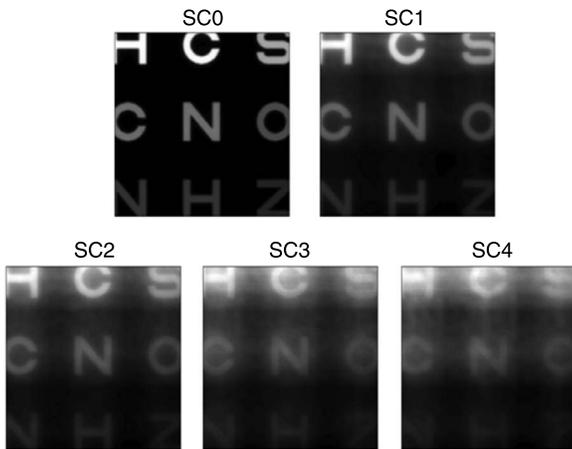


Figure 10. Example of simulated images for different amounts of increasing scatter (from SC0 to SC4).

positives values of RCD. A positive RCD indicates that a given combination of SA and defocus improves the contrast of the image with respect to the configuration without spherical aberration. The range of values of SA and defocus producing an improvement in the contrast of the image was similar as in the experiment with the artificial eye. However, for different amounts of scatter,

we found that the values of defocus and SA that actually improves contrast are different.

The results of these simulations were equivalent to those obtained from the experiment with the artificial eye: some small amounts of SA in combination with defocus can slightly improve the measured contrast on the image when the object is viewed through scatter. This further confirms that appropriate combinations of spherical aberration and defocus actually improved the contrast in the images when scatter was present. This is a purely optical effect due to the combination of aberrations and scatter.

We also carried out a psychophysical experiment to determine if this small optical effect could have some measurable impact in vision. Although the visual results were not as clear as the optical data from the artificial eye, they also showed a similar tendency. We found in some subjects that CS slightly increased when SA was added in the presence of scatter. This result may be counter-intuitive, since in general the addition of aberrations produces a reduction in visual performance. However, what is not surprising is to find compensation mechanisms between different optical parameters (Artal et al., 2001; McLellan, Prieto, Marcos, & Burns, 2006).

The balance between SA and scatter is even more appealing since they increase with age. In a similar way

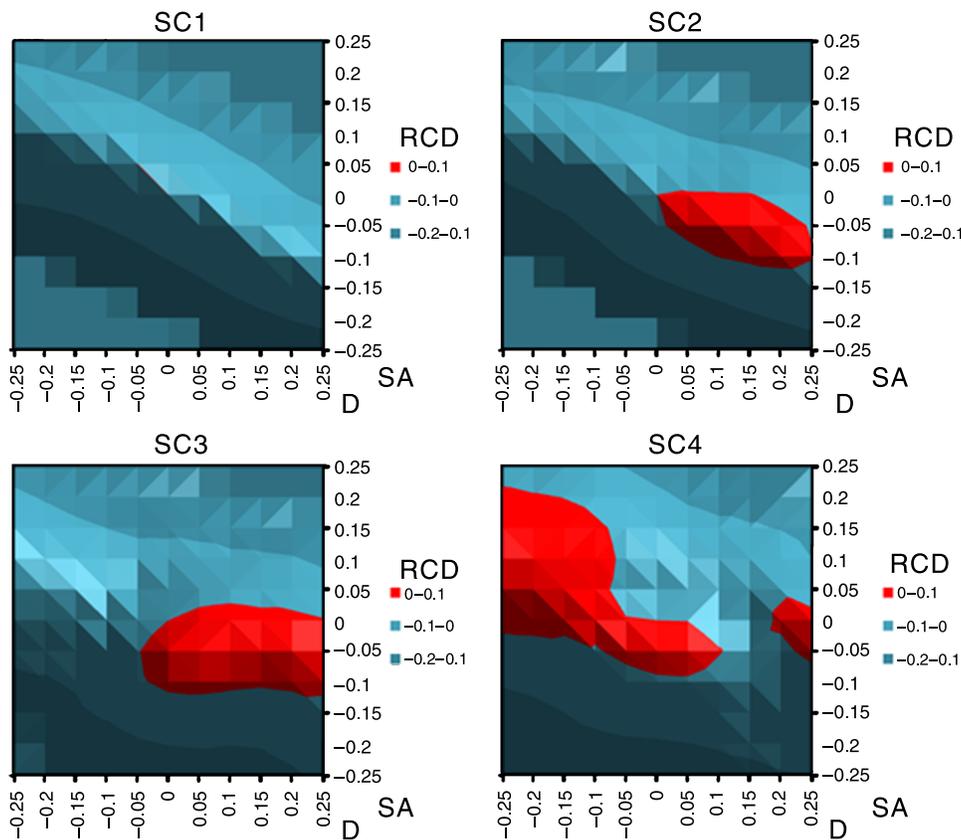


Figure 11. Relative contrast difference (RCD) as a function of defocus (in diopters) and spherical aberration (SA) in microns for ascending level of simulated scatter (SC1, low scattering; SC4, elevated scatter).

that with age, the average pupil size decrease reducing the impact of aberrations in the image contrast (Guirao et al., 1999), the coupling between scatter and spherical aberration may be also regarded as another compensatory mechanism to maintain image contrast in the older eye.

One important point to be discussed is the visual significance of our results. In other words, how important is the visual benefit of adding spherical aberration when the eye is affected by scatter? The RCSD parameter allowed us to directly quantify the relative effect produced by the addition of the selected amounts of SA on the CS. However, it is based in the subtraction of two similar values of contrast sensitivity that have inherent experimental errors. Error bars in Figures 5, 6, 8, and 9 were calculated from the standard deviation in the CS data. Without scatter, the addition of 0.15 μm of SA, which is a typical value in older eyes (Artal et al., 2002), reduces contrast sensitivity by around 30%. In the same subject and for the same aberration conditions, adding that amount of SA does not affect contrast sensitivity when scatter is present.

While we measured an actual effect in visual perception quantified through changes in contrast sensitivity, they must be associated with actual physical changes in the retinal images produced by the combination of scatter and aberrations. The degradation of the retinal image in the real eye with scatter and SA should be similar to that found in the artificial eye. It should be noted that we found more differences in retinal image contrast than in the CS.

We used an adaptive optics instrument to maintain the subjects' aberrations controlled during the measurements in order to assure that no other aberration components played a role in the results. The measurements were carried out for a pupil diameter of 4.8 mm. This diameter does not correspond with the average pupil diameter of an aged eye, which in general would be smaller due to the senile miosis.

Likewise, it has to be pointed out that the subjects searched for best focus in every tested condition. This introduced small changes in defocus, which depends on the amount of SA and on the subjects' own criteria. The contribution of these defocus shifts is not explicit in our results, but it is expected that under normal conditions some particular combinations of SA and defocus would produce the highest effect, as was actually the case in the artificial eye.

To reduce the number of variables, we performed the measurements in pseudo-monochromatic light. It is possible that under normal white light conditions the coupling effects of monochromatic and chromatic aberrations with scatter could be different and surely more complicated.

Another important aspect is the different nature of the scattering properties in the older eye and those produced by the diffusers used in this study. In the eye, scatter is produced in volume and not in a surface as in the used

diffusers. In addition, the amount of scatter in healthy older eyes may be lower than that used in the experiments.

From a practical point of view, and based on the results presented here, it could be argued on the convenience or not of adding spherical aberrations in ophthalmic devices, and in particular intraocular lenses (IOLs). This would be in an opposite direction of what has been suggested in recent years where aspheric intraocular lenses correcting the cornea spherical aberration were shown to produce the best visual performance (Guirao et al., 2002). In those situations where the level of scatter is small or moderate (as after IOL implantation), SA will always reduce performance, and in consequence, lenses correcting for the corneal SA should produce the highest quality of vision.

Conclusions

Ocular spherical aberration increases from around zero to positive values with age. Simultaneously, the presence of intraocular scattering also increases with age, although with a different temporal evolution. Both SA and scatter are known to decrease the quality of the retinal image and therefore spatial vision. We explored the combined effect of these factors on visual performance. We first showed in an artificial eye mounted on an optical bench that with scatter, the addition of SA under certain conditions may slightly improve image contrast. This could be regarded as a type of compensatory mechanism. To investigate whether this small optical effect could play some role in visual performance of older eyes, we performed an experiment measuring contrast sensitivity with an adaptive optics instrument that allowed us both to control aberrations and to induce different amounts of scatter with holographic diffusers. The contrast sensitivity we measured when adding SA was different with or without the presence of scatter. Contrast sensitivity was reduced less by scattering when SA was present as compared with the cases without SA. Although the visual effect is rather small, we can suggest that the combined presence of positive SA and scatter in the older eye could be a mild protective compensatory mechanism reducing the impact that the two factors may have on contrast vision separately.

Acknowledgments

This work has been supported in part by the *Ministerio de Educación y Ciencia* of Spain (Grants FIS2004-2153 and FIS2007-64765) and *Fundación Séneca* (Region de Murcia, Grant 4524/GERM/06).

Commercial relationships: none.

Corresponding author: Pablo Artal.

Email: pablo@um.es.

Address: Laboratorio de Optica, Centro de Investigacion en Optica y Nanofisica, Universidad De Murcia, Campus de Espinardo, 30071 Murcia, Spain.

References

- Applegate, R. A., Marsack, J. D., & Thibos, L. N. (2006). Metrics of retinal image quality predict visual performance in eyes with 20/17 or better visual acuity. *Optometry and Vision Science*, *83*, 635–640. [[PubMed](#)] [[Article](#)]
- Artal, P., Benito, A., & Tabernero, J. (2006). The human eye is an example of robust optical design. *Journal of Vision*, *6*(1):1, 1–7, <http://journalofvision.org/6/1/1/>, doi:10.1167/6.1.1. [[PubMed](#)] [[Article](#)]
- Artal, P., Berrio, E., Guirao, A., & Piers, P. (2002). Contribution of the cornea and internal surfaces to the change of ocular aberrations with age. *Journal of the Optical Society of America A, Optics, Image Science, and Vision*, *19*, 137–143. [[PubMed](#)]
- Artal, P., Chen, L., Fernández, E. J., Singer, B., Manzanera, S., & Williams, D. R. (2004). Neural compensation for the eye's optical aberrations. *Journal of Vision*, *4*(4):4, 281–287, <http://journalofvision.org/4/4/4/>, doi:10.1167/4.4.4. [[PubMed](#)] [[Article](#)]
- Artal, P., Ferro, M., Miranda, I., & Navarro, R. (1993). Effects of aging in retinal image quality. *Journal of the Optical Society of America A, Optics and Image Science*, *10*, 1656–1662. [[PubMed](#)]
- Artal, P., Guirao, A., Berrio, E., & Williams, D. R. (2001). Compensation of corneal aberrations by internal optics in the human eye. *Journal of Vision*, *1*(1):1, 1–8, <http://journalofvision.org/1/1/1/>, doi:10.1167/1.1.1. [[PubMed](#)] [[Article](#)]
- Atchison, D. A., Bradley, A., Thibos, L. N., & Smith, G. (1995). Useful variations of the Badal Optometer. *Optometry and Vision Science*, *72*, 279–284. [[PubMed](#)]
- Brown, N. (1974). The change in lens curvature with age. *Express Eye Research*, *19*, 175–183. [[PubMed](#)]
- Cowan (1995). Handbook of optics. In M. Bass (Ed.), *Fundamentals, techniques and design* (vol. 2, p. 27.1). New York: McGraw-Hill.
- Fernández, E. J., & Artal, P. (2005). Study on the effects of monochromatic aberrations in the accommodation response by using adaptive optics. *Journal of the Optical Society of America A, Optics, Image Science, and Vision*, *22*, 1732–1738. [[PubMed](#)]
- Fernández, E. J., Manzanera, S., Piers, P., & Artal, P. (2002). Adaptive optics visual simulator. *Journal of Refractive Surgery*, *18*, S634–S638. [[PubMed](#)]
- Guirao, A., González, C., Redondo, M., Geraghty, E., Norrby, S., & Artal, P. (1999). Average optical performance of the human eye as a function of age in a normal population. *Investigative Ophthalmology and Visual Science*, *40*, 203–213. [[PubMed](#)] [[Article](#)]
- Guirao, A., Redondo, M., & Artal, P. (2000). Optical aberrations of the human cornea as a function of age. *Journal of the Optical Society of America A, Optics, Image Science, and Vision*, *17*, 1697–1702. [[PubMed](#)]
- Guirao, A., Redondo, M., Geraghty, E., Piers, P., Norrby, S., & Artal, P. (2002). Corneal optical aberrations and retinal image quality in patients in whom monofocal intraocular lenses were implanted. *Archives of Ophthalmology*, *120*, 1143–1151. [[PubMed](#)]
- Hemenger, R. P. (1984). Intraocular light scatter in normal vision loss with age. *Applied Optics*, *23*, 1972. [[PubMed](#)]
- Hemenger, R. P., Garner, L. F., & Ooi, C. S. (1995). Change with age of the refractive index gradient of the human ocular lens. *Investigative Ophthalmology and Visual Science*, *36*, 703–707. [[PubMed](#)] [[Article](#)]
- IJspeert, J. K., de Waard, P. W., van den Berg, T. J., & de Jong, P. T. (1990). The intraocular straylight function in 129 healthy volunteers; dependence on angle, age and pigmentation. *Vision Research*, *30*, 699–707. [[PubMed](#)]
- Koretz, J. F., Handelman, G. H., & Brown, N. P. (1984). Analysis of human crystalline lens curvature as a function of accommodative state and age. *Vision Research*, *24*, 1141–1151. [[PubMed](#)]
- Körner, W., Scheller, H., Beck, A., & Fricke, J. (1994). PDLC films for control of light transmission. *Journal of Physics D: Applied Physics*, *27*, 2145–2151.
- Liang, J., & Williams, D. R. (1997). Aberrations and retinal image quality of the normal human eye. *Journal of the Optical Society of America A, Optics, Image Science, and Vision*, *14*, 2873–2883. [[PubMed](#)]
- Marcos, S., Moreno, E., & Navarro, R. (1999). The depth-of-field of the human eye from objective and subjective measurements. *Vision Research*, *39*, 2039–2049. [[PubMed](#)]
- Marsack, J. D., Thibos, L. N., & Applegate, R. A. (2004). Metrics of optical quality derived from wave aberrations predict visual performance. *Journal of Vision*, *4*(4):8, 322–328, <http://journalofvision.org/4/4/8/>, doi:10.1167/4.4.8. [[PubMed](#)] [[Article](#)]
- McLellan, J. S., Marcos, S., & Burns, S. A. (2001). Age-related changes in monochromatic wave aberrations

- of the human eye. *Investigative Ophthalmology & Vision Science*, 42, 1390–1395. [[PubMed](#)] [[Article](#)]
- McLellan, J. S., Marcos, S., Prieto, P. M., & Burns, S. A. (2002). Imperfect optics may be the eye's defence against chromatic blur. *Nature*, 417, 174–176. [[PubMed](#)]
- McLellan, J. S., Prieto, P. M., Marcos, S., & Burns, S. A. (2006). Effects of interactions among wave aberrations on optical image quality. *Vision Research*, 46, 3009–3016. [[PubMed](#)]
- Navarro, R. (1985). Incorporation of intraocular scattering in schematic eye models. *Journal of the Optical Society of America A, Optics and Image Science*, 2, 1891–1894. [[PubMed](#)]
- Pérez, G. M., & Artal, P. (2006). *Investigative Ophthalmology and Visual Science*, 47, E-Abstract 1217.
- Piers, P. A., Fernandez, E. J., Manzanera, S., Norrby, S., & Artal, P. (2004). Adaptive optics simulation of intraocular lenses with modified spherical aberration. *Investigative Ophthalmology & Visual Science*, 45, 4601–4610. [[PubMed](#)] [[Article](#)]
- Piers, P. A., Manzanera, S., Prieto, P. M., Gorceix, N., & Artal, P. (2007). Use of adaptive optics to determine the optimal ocular spherical aberration. *Journal of Cataract and Refractive Surgery*, 33, 1721–1726. [[PubMed](#)]
- Prieto, P. M., Vargas-Martín, F., Goelz, S., & Artal, P. (2000). Analysis of the performance of the Hartmann–Shack sensor in the human eye. *Journal of the Optical Society of America A, Optics, Image Science, and Vision*, 17, 1388–1398. [[PubMed](#)]
- Rocha, K. M., Nosé, W., Bottós, K., Bottós, J., Morimoto, L., & Soriano, E. (2007). Higher-order aberrations of age-related cataract. *Journal of Cataract and Refractive Surgery*, 33, 1442–1446. [[PubMed](#)]
- Smith, G., Atchison, D. A., & Pierscionek, B. K. (1992). Modeling the power of the aging human eye. *Journal of the Optical Society of America A, Optics and Image Science*, 9, 2111–2117. [[PubMed](#)]
- Villegas, E., Alcón, E., & Artal, P. (2008). Optical quality of the eye in subjects with normal and excellent visual acuity. *Investigative Ophthalmology & Visual Science*, 49, 4688–4696. [[PubMed](#)]
- Wadle, S., & Lakes, R. S. (1995). Holographic diffusers: Diffusers with low backscatter. *Journal of Modern Optics*, 42, 1387–1396.
- Westheimer, G., & Liang, J. (1994). Evaluating diffusion of light in the eye by objective means. *Investigative Ophthalmology & Visual Science*, 35, 2652–2657. [[PubMed](#)] [[Article](#)]
- Westheimer, G., & Liang, J. (1995). Influence of ocular light scatter on the eye's optical performance. *Journal of the Optical Society of America A, Optics, Image Science, and Vision*, 12, 1417–1424. [[PubMed](#)]
- Yoon, G., & Williams, D. R. (2002). Visual performance after correcting the monochromatic and chromatic aberrations of the eye. *Journal of the Optical Society of America A, Optics, Image Science, and Vision*, 19, 266–275. [[PubMed](#)]