

# Contrast sensitivity benefit of adaptive optics correction of ocular aberrations

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While correcting the aberrations of the eye produces large increases in retinal image contrast, the corresponding improvement factors in the contrast sensitivity function have been little explored and results are controversial. We measured the CSF of 4 subjects with and without correcting monochromatic aberrations. Monochromatic CSF measurements were performed at four orientations (0, 45, 90, and 135 deg) and at six spatial frequencies (2–30 c/deg). In two subjects, the CSF was also measured in polychromatic light. The MTF increased on average by 8 times and meridional changes in improvement were associated to individual meridional changes in the natural MTF. CSF increased on average by 1.35 times (only for the mid- and high spatial frequencies) and was lower (0.93 times) for polychromatic light. Under natural aberrations, the horizontal and vertical CSFs tended to be higher than the oblique CSFs, but the meridional differences in the CSF were partially reduced when the aberrations were corrected. The consistently lower benefit in the CSF than in the MTF of correcting aberrations suggests a significant role for the neural transfer function in the limit of contrast perception. Polychromatic aberrations play an additional role in degrading contrast, particularly in the absence of monochromatic high-order aberrations.

Keywords: CSF, MTF, adaptive optics, ocular high-order aberrations, adaptation

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## Introduction

The advent of laser systems and interferometry in the 1960s allowed determination of the neural contrast sensitivity function by bypassing the optics of the eye (Campbell & Green, 1965). Recently, adaptive optics has allowed the projection of any type of stimulus to the retina under corrected optical aberrations. Several studies have studied the visual benefit of correcting high-order aberrations on visual acuity (Dalimier, Dainty, & Barbur, 2008; Marcos, Sawides, Gamba, & Dorronsoro, 2008; Yoon & Williams, 2002) and other visual tasks such as familiar face recognition (Sawides, Gamba, Pascual, Dorronsoro, & Marcos, 2010). An improvement in visual performance is observed in the majority of the cases, although to which extent the visual system exploits the increase of optical quality is not fully clear. Despite the expected direct improvement of the contrast sensitivity function (CSF) by improvement of the modulation transfer function (MTF)

upon correction of optical aberrations, this has been relatively little explored, and the relationship between the improvement in the MTF and the corresponding improvement in the CSF is somewhat controversial. In their seminal work, Liang, Williams, and Miller (1997) showed a maximum increase in the CSF by a factor of 6 for 27.5 c/deg, although comparisons between MTF and CSF improvements were not reported. In another work, Yoon and Williams (2002) showed improvements of CSF up to a factor of 3 in one subject and up to 5 in another when the improvements predicted by the MTF calculations were up to a factor of 20. A recent study compared the improvement in the CSF and MTF for different age groups with correction of optical aberrations and found that although the CSF values were lower for older observers they did benefit more from the AO correction than younger observers (Elliott et al., 2009). They found optical benefits of up to a factor of 2 for a spatial frequency of 18 c/deg, slightly lower than the visual benefit that they found in the CSF (factor of 2.5 for the

same spatial frequency of 18 c/deg). On the other hand, another study reported similar increases (by up to a factor of 8) both in the CSF and the MTF, although it appears that both the CSF and MTF improvements were not defined similarly (Murray et al., 2010). However, most of the studies reported a much higher AO/no AO ratio for the MTF than for the CSF (Guo, Atchison, & Birt, 2008; Legras & Rouger, 2008; Yoon & Williams, 2002). Yoon and Williams attributed the differences to imprecision in the AO corrections.

On the other hand, the CSF measured after correction of aberrations should not exceed the neural transfer function. Campbell and Green measured this function by direct projection of interference fringes on the retina. The reported ratio of the standard CSF (under natural viewing) and the CSF measured by bypassing the optics of the eye (neural CSF) ranged from 1 for spatial frequencies lower than 5 c/deg to 5 at 40 c/deg (for 5.8-mm pupils). These values would represent an upper limit to the improvement of CSF expected when correcting the optical aberrations of the eye.

Classical studies showed differences in the CSF thresholds at different orientations. Typically, the horizontal CSF exceeds the vertical CSF, and the CSF is lowest for oblique orientations. This phenomenon has been known as the “oblique effect” (Campbell & Kulikowski, 1966; Furchner & Young, 1975). These psychophysical measurements have a good correspondence with the preferred neuron selectivity to different orientations shown by neurons in the visual cortex (Li, Peterson, & Freeman, 2003). Interestingly, it has been shown that perceptual learning can improve the orientation selectivity of neurons in the primary visual cortex effectively promoting spatial interactions and resulting in an increase in contrast sensitivity, suggesting that not only optical and physiological factors but also neuronal plasticity of the visual cortex in adults play a role in perceptual contrast sensitivity (Hua et al., 2010; Huang, Zhou, & Lu, 2008). On the other hand, a recent study by Murray et al. (2010) postulates that optical factors could contribute to this oblique effect.

In this study, we will explore the limits of the visual improvement due to the optical improvements in retinal image quality by measuring the CSF in monochromatic and polychromatic conditions under natural aberrations and after AO correction for a wide range of angles and frequencies.

## Methods

### Adaptive optics setup

A custom-developed adaptive optics system was used in the study to correct and induce selected aberrations. The

system has been described in detail in previous publications (Atchison, Guo, Charman, & Fisher, 2009; Atchison, Guo, & Fisher, 2009), where the OLED display was replaced by a projector (Epson EMP 1810 multi-media projector) and a high resolution rear projection screen (Novix Systems, Praxino rear projection screen) placed at a distance of 3 m from the exit conjugated pupil plane. In brief, the main components of the system are a Hartmann–Shack wavefront sensor (composed by  $42 \times 32$  microlenses of which 415 were used to measure our 5.2-mm pupils, with 15-mm effective diameter and a CCD camera; HASO 32 OEM, Imagine Eyes, France) and an electromagnetic deformable mirror (MIRAO 52d, Imagine Eyes, France). The desired mirror states were achieved by a closed-loop operation. Visual stimuli were presented by the gamma-corrected projector on the rear projection screen, viewed through the AO mirror, and a Badal system. The stimuli were Gabor patches (standard deviation: 0.66 deg). The generation of stimuli was controlled by a Cambridge Research Systems VSG card. The mean luminance at the pupil plane was  $50 \text{ cd/m}^2$  and the total magnification of the system was  $\times 0.5$ .

### Subjects

Four subjects aged 28 to 56 years were tested. Subjects S1 and S2 were two of the authors and experienced observers in psychophysical trials. Subjects S3 and S4 were naive and unacquainted with the purpose of the study. Table 1 shows the refractive profile of the subjects.

### Experimental protocol

Subjects were instilled with one drop of 1% cyclopentolate 20 min before the experiment started, with one additional drop applied every 90 min.

Before the CSF measurements, the focus setting for each condition (all aberrations corrected, natural aberrations, natural aberrations with astigmatic correction) was determined. The subjects were asked to find the best focus while viewing a Maltese cross target, by moving a Badal system.

Subject #	Age	Defocus (D)	Astigmatism (D)	Angle (deg)
S1	56	−2.25	−0.25	50
S2	28	0.25	−0.25	170
S3	28	0	0	–
S4	29	0	−0.25	90

Table 1. Age and refractions of the subjects of the study.

The setting was repeated 5 times, and the average was taken as the correcting focus setting.

CSFs were measured for six spatial frequencies (1.9, 3.8, 7.6, 15.2, 22.7, and 30.3 c/deg) and four orientations (0, 45, 90, and 135 deg) with a staircase (2 down/1 up) four-alternative forced choice procedure (4 orientations for a fixed frequency) in steps of 0.05 log contrast. Measurements started between 0.2 and 0.4 log unit above threshold and were considered finished after 7 reversals were completed, and the threshold was determined from the average of the last 6 reversals. The stimulus was presented after an auditory tone during 0.5 s. Each measurement was repeated 3 times and deemed satisfactory if the standard deviation of the trials was less than 0.2 log unit; most standard deviation was less than 0.1 log unit. Measurements with and without AO correction of aberrations were randomized. For each spatial frequency, four simultaneous staircase procedures were interleaved (one for each orientation). Aberrations were corrected across a 5.2-mm pupil. An artificial stop projected to the eye provided a 5-mm pupil for viewing the visual display.

Aberrations were measured immediately before and after a CSF measurement. A closed-loop correction was generated immediately before and after the CSF measurements for the AO condition.

Monochromatic CSF measurements were performed by placing an interference filter (peak transmission, 550 nm; FWHM, 10 nm). Polychromatic CSF measurements were performed for the extended spectral range of the projector lamp (EPSON EMP1810). In order to achieve luminance values at the pupil plane in the polychromatic conditions, equal to that in monochromatic condition, the interference filter was replaced by a neutral density filter (ND 1.3).

Each complete CSF measurement took about 4 h (including all frequencies, angles, and 3 repetitions). Measurements were conducted for monochromatic and polychromatic light (2 subjects), AO and non-AO corrected (all 4 subjects), and astigmatism corrected (2 subjects). Subjects were allowed to take breaks during the session. A complete set of data per subject was collected in between 2 and 5 sessions. Before the actual runs, a training session was conducted (with only one frequency) in order to familiarize the subjects with the protocols and tasks.

## Wave aberrations and MTF calculations

Wave aberrations were fitted by 7th-order Zernike polynomials. The coefficients were measured for a 5.2-mm pupil and then rescaled for a 5-mm pupil. The MTF calculations were performed using standard Fourier optics in Matlab (Mathworks, Naticks, MA) from the wave aberrations, for 5.0-mm circular pupils and 550-nm wavelength. The defocus term was set to 0 for the AO-corrected aberrations and to the value corresponding to the defocus setting shift (with respect to the AO condition) for any

other condition. For the MTF calculations, the average of the Zernike coefficients measured before and after a set of CSF measurement was used.

## Results

### Measurement and correction of ocular aberrations

Insets in [Figure 1](#) show the wave aberrations (natural and AO-corrected) for the four subjects of the study. Tilts and defocus were set to zero for representation. The RMS of the 4 subjects decreased after correction of their aberrations to an average of 20% of the natural RMS. [Figure 1](#) shows the corresponding RMS values for natural and AO-corrected wave aberrations (5-mm pupils) and the percentage of correction.

The wave aberrations and RMS values shown in [Figure 1](#) correspond to averages of 36 repeated measurements throughout the experiment. RMS standard deviations range from 0.05 to 0.07  $\mu\text{m}$ .

### MTF and CSF measurements

[Figure 2](#) shows 2-D MTFs and [Figure 3](#) shows 2-D CSFs for the 4 subjects with their natural aberrations (no AO) and after the correction of their high-order aberrations and astigmatism. The MTFs were computed from the wave aberrations at the same focus as for the CSF measurements. The CSFs are interpolations for measurements at the selected spatial frequencies and orientations. With correction of astigmatism and HOA, there is an increase in the symmetry of the MTF, increase in contrast, and a clear extension of the spatial frequency range. The oblique effect (less sensitivity at 45 and 135 deg) in the CSF is apparent both in the uncorrected and AO-corrected CSFs. There is a slight extension in the CSF spatial frequency range with correction.

The achieved levels of optical correction were 80%, 63%, 81%, and 87% for S1, S2, S3, and S4, respectively. These values are relative to the diffraction-limited MTF and were averaged across angles and between 1.9 and 30.3 c/deg.

The MTFs at 0- and 90-deg orientations are higher by 10% than the MTF at 45 and 135 deg, for natural aberrations. However, the difference between horizontal/vertical and oblique meridians decreases to 1% when all aberrations are corrected. On the other hand, the CSF is higher at 0/90 deg than at 45/135 deg both for natural aberrations (by 10%) and after correction of aberrations (by 8%). These data are averaged across subjects and spatial frequencies (from 1.9 to 30.3 c/deg range for the MTF and all the measured spatial frequencies of the CSF).

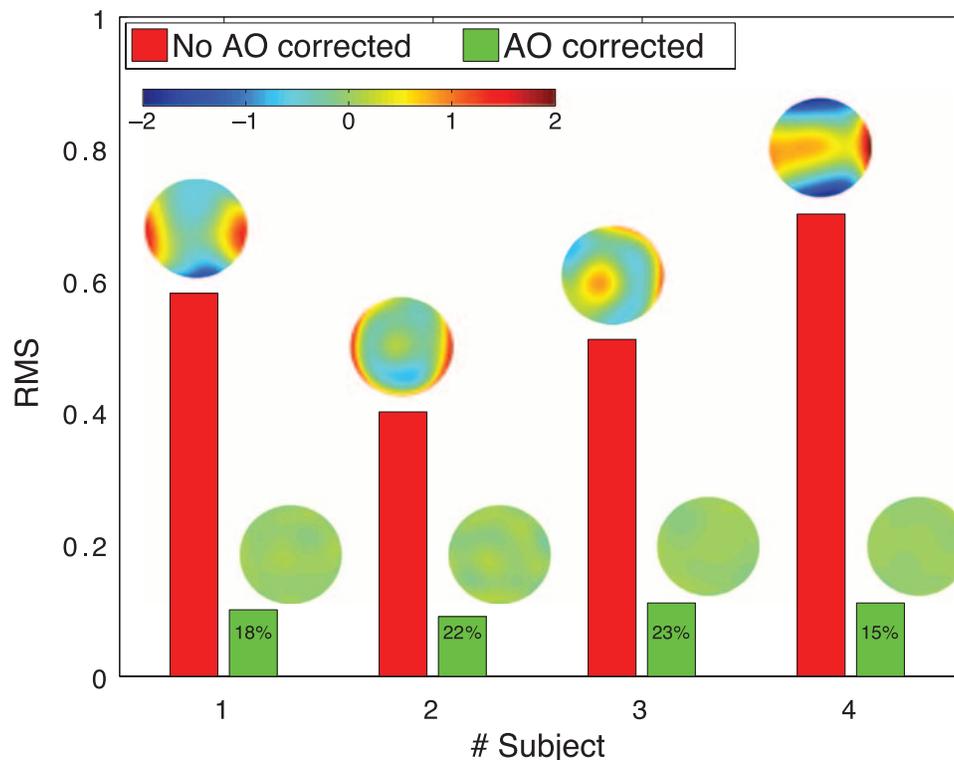


Figure 1. RMS values of the four subjects, with natural aberrations (red) and after AO correction (green). Insets over each bar show the average wavefront of 36 repeated measurements. The color bar shows the wave aberration scale in microns (same for all maps). The percentages represent the level of correction with respect to the natural aberrations of the subjects.

### MTF and CSF improvements with AO correction as a function of spatial frequency

Figure 4 shows the improvement with AO correction in the MTF ( $MTF_{AO}/MTF_{NoAO}$ ) and in the CSF ( $CSF_{AO}/CSF_{NoAO}$ ) as a function of spatial frequency and a comparison of the MTF and CSF ratios (with the  $y$ -axis appropriately scaled to make them comparable). The MTF improves on average by a factor of 8 and the CSF on average by a factor of 1.15. The improvement in the MTF increases steadily with spatial frequency (from  $\times 1.1$  at 1.9 c/deg to  $\times 15$  at 30.2 c/deg). The CSF increases only for spatial frequencies higher than 7.6 c/deg (e.g., by  $\times 1.52$  at 22.7 c/deg). For intermediate spatial frequencies, the improvement in the CSF and MTF correlate well (although they differ by a factor of 7) but not for the lowest and highest spatial frequencies.

### MTF and CSF improvements with AO correction as a function of orientation

Figure 5 shows the improvements with AO correction in the MTF ( $MTF_{AO}/MTF_{NoAO}$ ) and in the CSF ( $CSF_{AO}/CSF_{NoAO}$ ) as a function of orientation and a comparison of the MTF and CSF ratios (with the  $y$ -axis appropriately

scaled to make them comparable). Data are averaged across central frequencies (15.2 and 22.7 c/deg) and subjects. On average, there is a relatively good match between the most improved meridians (45 and 135 deg) and least improved meridians (0 and 90 deg) in both the MTF and CSF.

At the individual level, although the improvement in the oblique orientations are higher than at 0/90 deg orientation, the AO-corrected CSFs are lower than in the oblique meridians than at 0/90 deg.

Figure 6 shows radial profiles of Figures 2 and 3 for the individual subjects. These graphs show that the values at 0 and 90 degrees are higher than those obtained at 45 and 135 degrees for the natural aberration condition, both for the MTF (10%) and the CSF (10%). While this meridional difference is still present for the CSF after AO, it is not in the MTF (1%).

### CSF improvements in polychromatic conditions

Figure 7 compares the improvements in monochromatic and polychromatic CSFs, as a function of spatial frequency and angles. The average improvement in polychromatic light is consistently lower for all subjects and

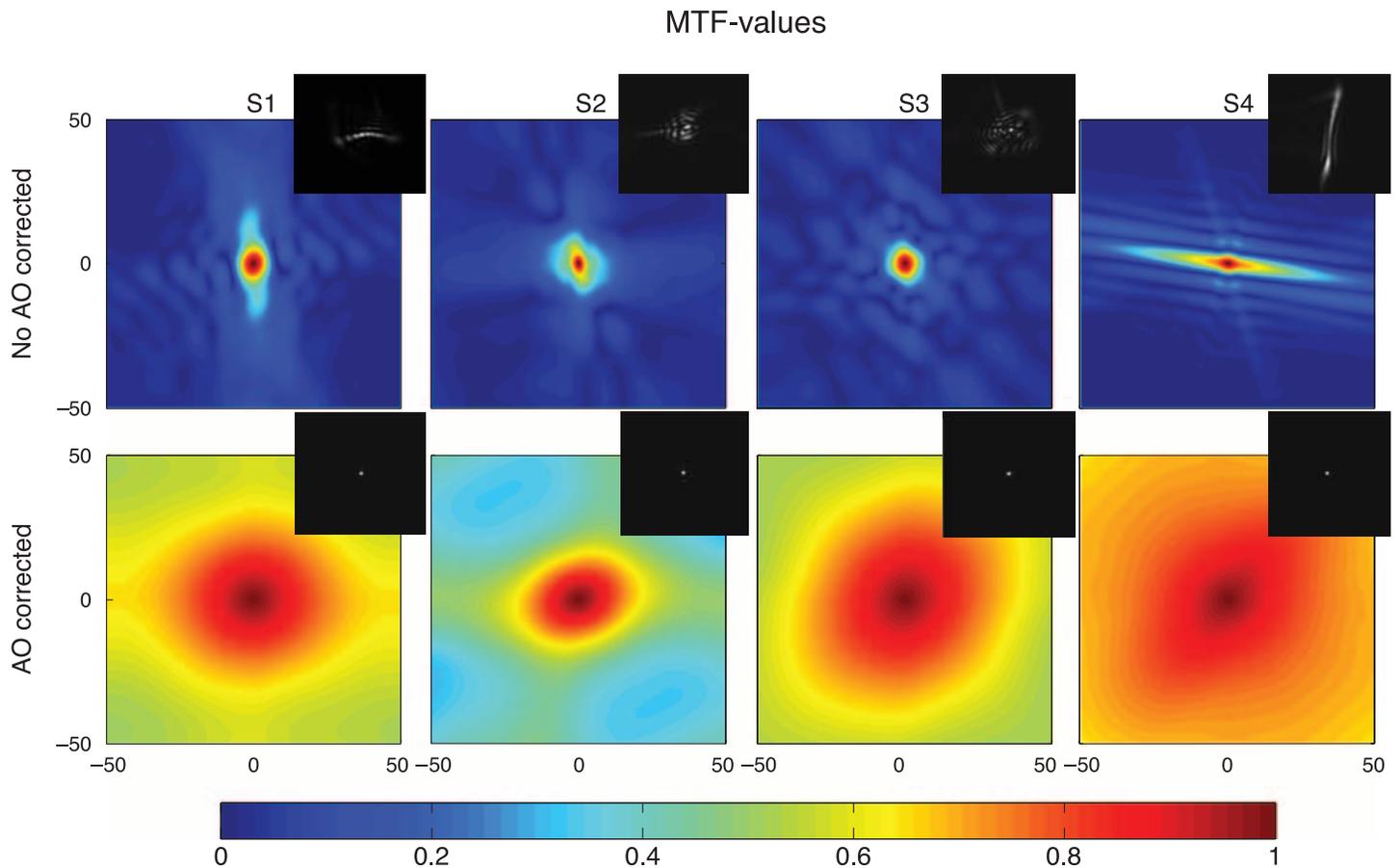


Figure 2. Two-dimensional MTFs for the four subjects of the study. Upper row: Under natural aberrations. Lower row: Under AO correction of astigmatism and HOA and their corresponding PSFs (insets). Data are for best subjective focus in each condition. MTFs are represented up to  $\pm 50$  c/deg. PSF window size =  $50 \mu\text{m}$ .

angles (averaged across frequencies) and for most of the spatial frequencies (averaged across angles) than under monochromatic conditions (ratio of improvements mono/poly =  $1.2 \pm 0.2$ ).

## Discussion

We have shown improvements in contrast sensitivity upon correction of HOA. However, despite a large increase in the modulation transfer function (by a factor of 8 at intermediate spatial frequencies), the corresponding improvement in the contrast sensitivity function (by a factor of 1.4) is minor, for 5-mm pupils. The AO-corrected MTF is close to diffraction limit (within 80% on average across subjects), with the difference likely arising from residual aberrations. The lack of correspondence between the improvement in the MTF and CSF has been reported by some but not all studies. Yoon and Williams (2002) reported an improvement in the CSF by  $\times 6$  in one subject

and  $\times 3$  in another subject, for 6-mm pupils, where the expected improvement in the MTF was  $\times 20$  times. They attributed the lower apparent performance in the CSF than in the MTF to the fact that the MTFs were only calculated from a single measurement of aberrations, measured at the beginning of the session. We minimized this potential source of error by using the average of the set of Zernike coefficients measured at multiple times throughout the session. Although we cannot rule out a perfect correspondence between the actual retinal image quality and that solely predicted by the measured aberrations in the real eye (as image quality was not monitored using an independent channel and this may be affected by scattering, fluctuations, or residual aberrations), control experiments using an artificial eye showed a good match between the captured image and that predicted by the aberrations induced on the mirror and measured with the wavefront sensor. Other studies suggested a good correspondence between the increase in the optical and perceptual contrast. Murray et al. (2010) used a metric expressed in dB for the CSF improvement (which implied multiplication by a factor of 20) but not for the MTF and

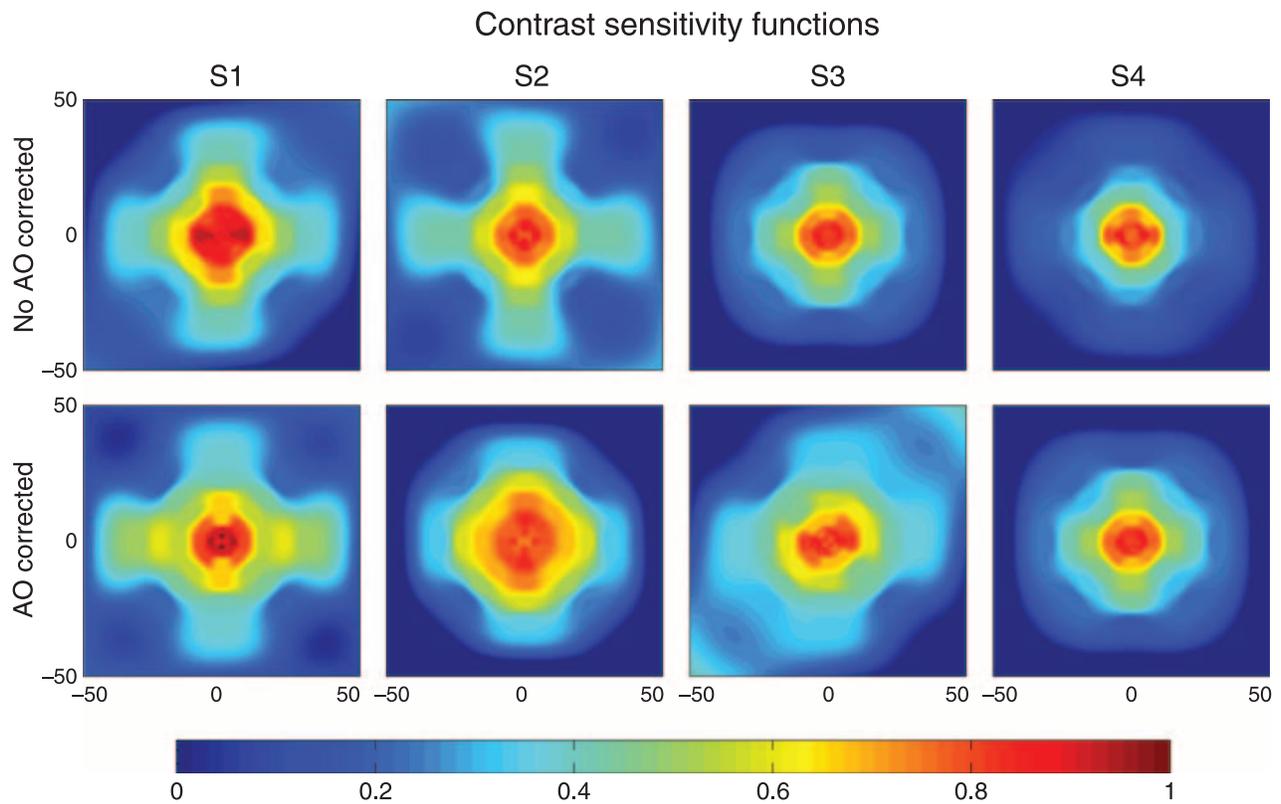


Figure 3. Two-dimensional CSFs (linear interpolations) for the four subjects. Upper row: Under natural aberrations. Lower row: Under AO correction of HOA and astigmatism, for best subjective focus in each condition. CSFs are represented up to  $\pm 50$  c/deg. Each of the subject's data (AO and no AO) has been normalized by its maximum value.

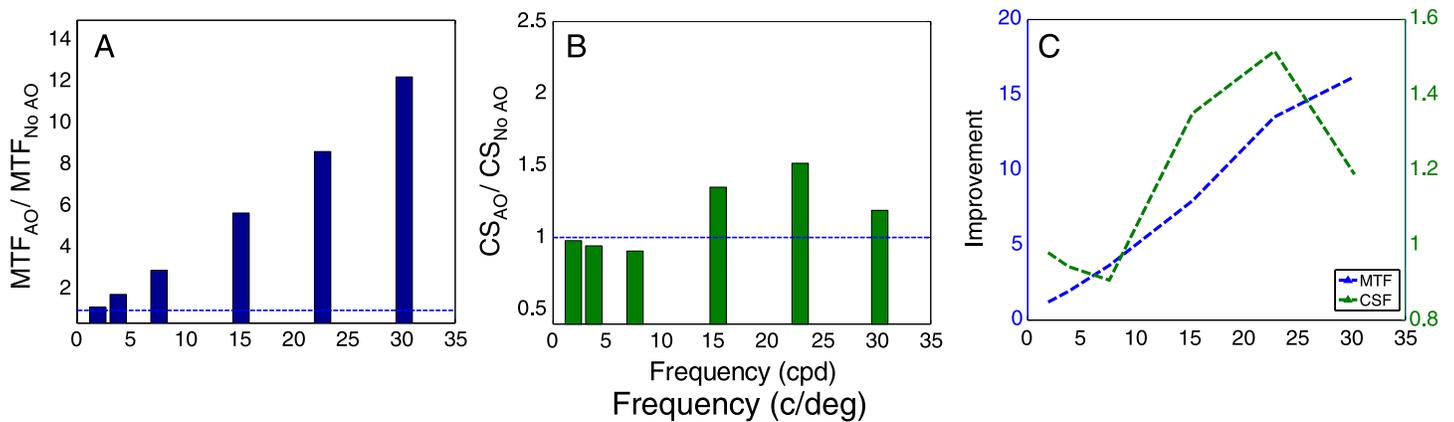


Figure 4. (A) MTF AO/no AO ratios and (B) CSF AO/no AO ratios as a function of spatial frequency, averaged across orientations and subjects. (C) Comparative AO/no AO ratios for the MTF (in blue) and the CSF (in green).

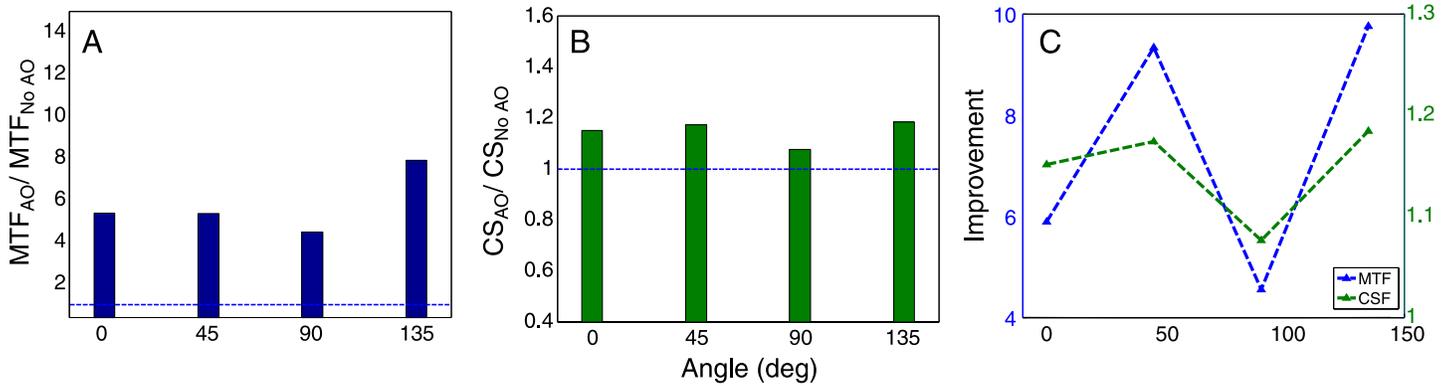


Figure 5. (A) MTF AO/no AO ratios and (B) CSF AO/no AO ratios, as a function of angle, averaged across frequencies and subjects. (C) Comparative AO/no AO ratios, for the MTF (in blue) and the CSF (in green), averaged across frequencies and subjects.

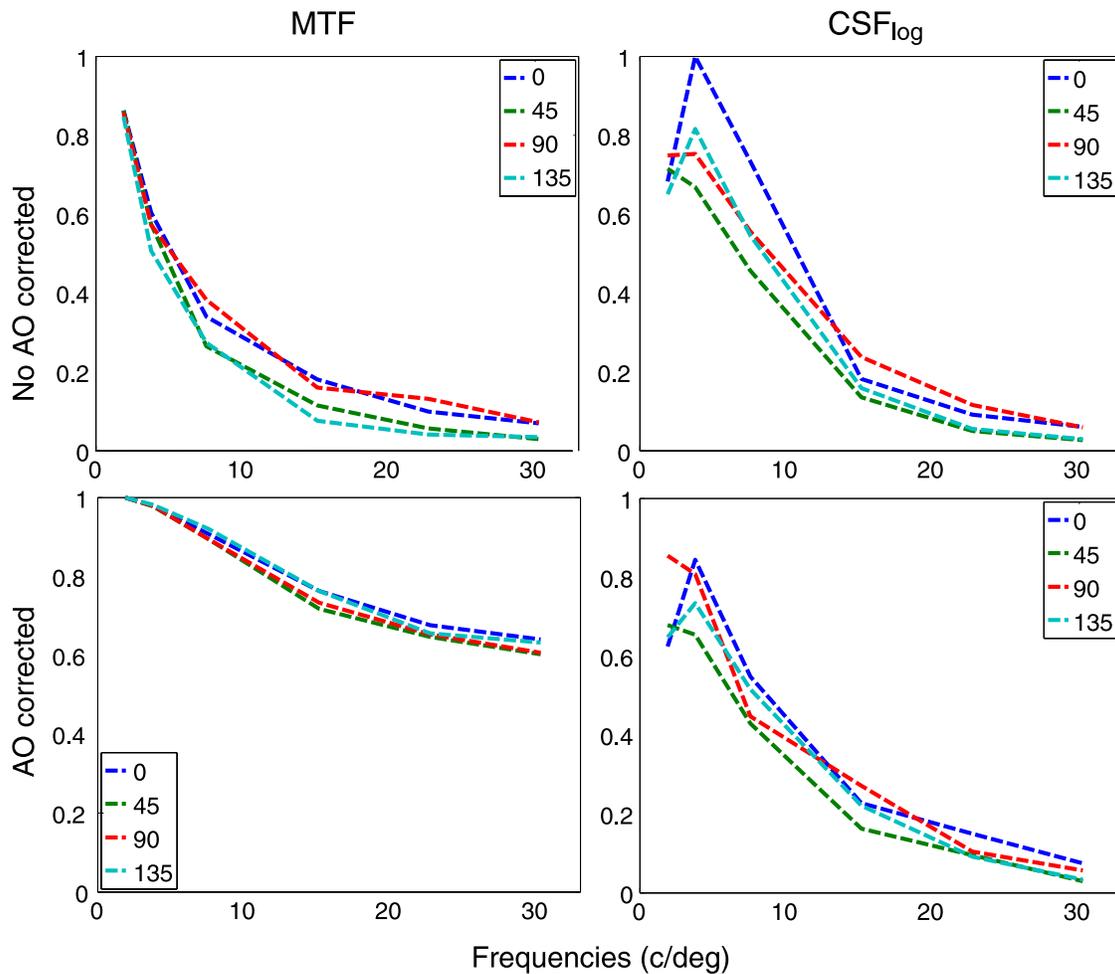


Figure 6. MTF (left column) and CSF (right column) cross-sections (at 0-, 45-, 90-, and 135-deg meridians) for natural aberrations (upper row) and AO-corrected aberrations (lower row), for all subjects.

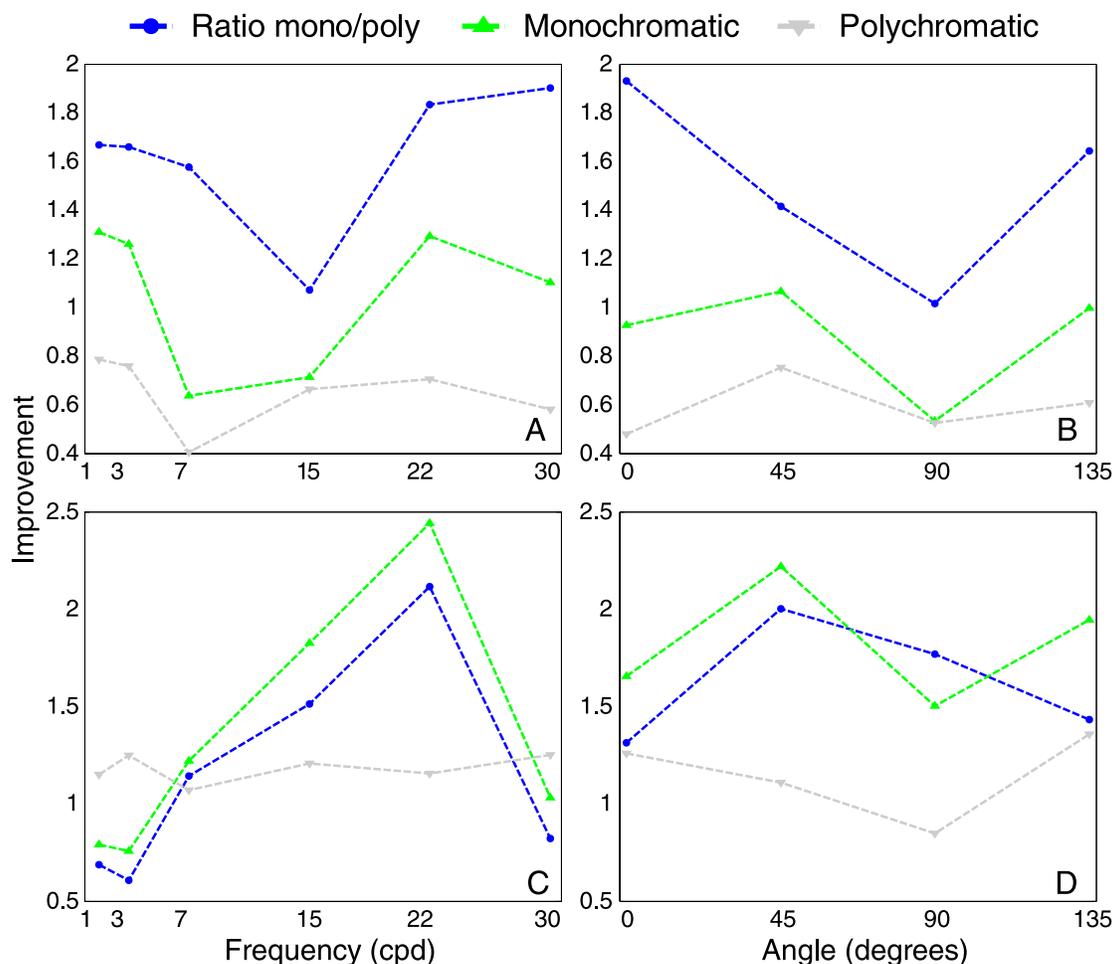


Figure 7. CSF AO/CSF no AO for monochromatic (green line) and polychromatic (gray line) light for Subjects 1 (top) and 2 (bottom), averaged across angles as a function of the frequency (left column) and averaged across central frequencies (7.6, 15.2, and 22.7 c/deg) as a function of the angle (right column).

found a correlation between the improvement in the CSF and the MTF for spatial frequencies of 12 and 16 c/deg and 6-mm pupils, with a slope near 1. On the other hand, another study reported optical improvements ranging from 1 to 3 times for spatial frequencies ranging from 1 to 18 c/deg, which were comparable or in fact slightly lower than the improvements found in the CSF, for 6-mm pupils (Elliott et al., 2009). It is not clear to which extent the optical computations (which involved convolutions of the Gabor targets with the estimated MTFs) differed from direct calculations of the MTFs. Most of the studies focused on low and intermediate spatial frequencies. The lack of improvement in the CSF for low spatial frequencies is consistently found in all studies. Yoon and Williams also reported relative less improvement for the highest spatial frequencies, as we also found in the current study.

An excellent match between the CSF ratio and MTF ratio following a change in the optics has been widely reported,

when the change consisted of an optical degradation, such as defocus (Atchison & Scott, 2002; Atchison, Woods, & Bradley, 1998; Rouger, Benard, & Legras, 2010; Woods, Bradley, & Atchison, 1996), or an increase in the optical aberrations, i.e., induced by LASIK surgery (Marcos, 2001). A decrease in the MTF therefore seems to produce a similar decrease in the CSF. However, the results of our study (as that of Yoon & Williams, 2002) suggest that an increase in the MTF (producing almost diffraction-limited retinal image) does not produce a similar increase in the CSF. The limits imposed by the neural CSF are likely the reason for this moderate improvement in the CSF, as the corrected CSF cannot exceed neural limits.

Campbell and Green (1965) found that the ratio between the CSF measured with interference fringes and the one obtained through the natural optics of the eye was almost one for low frequencies and went up to  $\times 5$  at 40 c/deg (for 5.8-mm pupils). These results are consistent with the CSF AO-corrected/CSF natural ratios of our study (up

to  $\times 4$  for Subject 2 and 22.7 cpd for 5-mm pupils) and those found by Yoon and Williams (2002; up to  $\times 5$  for 6-mm pupils).

Our results are consistent with the well-accepted neural origin of the oblique effect. The lower CSFs at 45 and 135 deg (relative to 0 and 90 deg) also occur under AO correction of aberrations, despite rather symmetric AO-corrected MTFs. On the other hand, the fact that the AO/no AO ratios show similar dependencies with meridian (Figure 6) is indicative of some optical contribution to the oblique effect under natural aberrations, as in these subjects the natural MTF is on average higher at 0 and 90 deg than at 45 and 135 deg. Interestingly, all our subjects showed better optics at 0/90 deg than 45/135 deg. Whether the higher neural specialization in the visual cortex at 0/90 deg arises from a typically better optical quality at this orientation is still an open question (Murray et al., 2010; Tahir, Parry, Brahma, Ikram, & Murray, 2009; Timney & Muir, 1976). Alternatively, our data (particularly in Subject 4) are suggestive of visual adaptation mechanisms that overcome some of the optical losses at specific orientations. S4 shows a highly anisotropic MTF (horizontal meridian shows MTF values 2.58 times higher than the vertical), whereas the CSF tends to be much more symmetric. While a shift in the defocus (by 0.20  $\mu\text{m}$ ) would have led to a more symmetric MTF, at the circle of least confusion, repeated measurements on this subject confirmed the subjective focus preference of this subject at the selected defocus setting (used in the MTF computations and CSF measurements). A potential explanation to the apparent better visual performance at the optically degraded astigmatism is adaptation to astigmatism. In a recent study, we have shown a relative insensitivity to astigmatism in habitually non-corrected astigmats, which led to a better visual acuity than that predicted optically and better than the visual acuity of non-astigmats with equivalent induced astigmatism (de Gracia, Dorronsoro, Marin, Hernández, & Marcos, 2011). These results are consistent with an early study where the notches of the CSF in the presence of astigmatism can be relatively well predicted by the optics, as in that study astigmatism was induced and not naturally present in the subjects (Apkarian, Tijssen, Spekreijse, & Regan, 1987). Interestingly, in that study, the sensitivity loss produced by astigmatism occurred in a relatively narrow spatial frequency band (5 c/deg) that we could have missed in the frequencies tested. We measured the CSF under correction of astigmatism in 2 of the subjects of the study with significant natural astigmatism (S1 and S2), while leaving the HOA uncorrected. We did not find significant differences with respect to the CSF measured under natural aberrations (ratio = 1.01), suggesting an adaptation to the natural astigmatism in these subjects.

As expected, the benefit of AO correction on the CSF was less in polychromatic than in monochromatic light. Chromatic aberrations have more deleterious effects on the optics in the absence of HOA than under natural aberrations

(Marcos, Burns, Moreno-Barriuso, & Navarro, 1999; McLellan, Marcos, Prieto, & Burns, 2002), and the expected MTF AO/no AO is lower in polychromatic light.

## Conclusions

We compared the optical improvement of correcting high-order aberrations and astigmatism using adaptive optics with the visual improvement in the contrast sensitivity:

1. The optical benefit (in the MTF) exceeds the visual benefit (in the CSF) by a factor of 5. The improvement in the CSF by near diffraction-limited optics appears to be limited by neural contrast sensitivity.
2. Although the trend of the CSF results under AO correction is well described by the MTF, the magnitude of the impact of the correction is overestimated.
3. The largest benefit in the CSF occurs at intermediate spatial frequencies.
4. The relatively lower CSF at 45/135 deg after correction of the optical aberrations (despite the isotropic AO-corrected MTF) confirms the neural origin of the oblique effect. The tendency for a better optical quality at 0/90 deg might suggest an optical role in the neuronal meridional selectivity in the visual cortex.
5. The lack of meridional correspondence in the MTF and CSF in subjects with natural astigmatism suggests spatial adaptation to astigmatism in these subjects.
6. The benefit of aberration correction in the CSF decreases in polychromatic light.

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