Higher-order aberrations produce orientation-specific notches in the defocused contrast sensitivity function

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Local minima or notches in the defocused contrast sensitivity function (CSF) have been linked to the aberrations of the eye. We use theoretical modeling of the effects of the aberrations to show these notches can be orientation-selective due to the effects of aberration terms such as coma and trefoil. Notches that changed with orientation were observed in the defocused CSF of four subjects. The measured CSFs were found to match well with theoretical predictions produced using the individual aberrations. Theoretical modeling highlighted orientation-specific differences in notches for both positive and negative blur. The results indicate that orientation is an important variable when testing for the functional effects of higher-order aberrations.

Keywords: contrast sensitivity, physiological optics, spatial vision, higher-order aberrations, orientation


Introduction

The contrast sensitivity function (CSF) can display local areas of minima or ‘notches’ of selective spatial frequency loss. Such notches can be produced due to neural conditions such as retinal disease, optic nerve disease and cerebral lesions (Bodis-Wollner & Diamond, 1976; Regan, Silver, & Murray, 1977). Notches in the CSF may also have an optical origin. When sufficient defocus is added to a defraction limited optical system, undulations in the modulation transfer function (MTF) will be produced, with the MTF dropping from a value of 1.0 at zero spatial frequency to zero at another spatial frequency before rising again (Hopkins, 1955). Figure 1a shows such notches in the MTF for an aberration free—defraction limited model eye of pupil size 6 mm when blur of +1DS and −1DS is added. When blur is added in the presence of aberrations, these notches shift in both position and depth and this is shown using the aberrations of a normal eye with a 6 mm pupil in Figure 1b.

Many studies, notably Green and Campbell (1965) and Charman (1979), have investigated the effect of blur on the CSF. Atchison, Woods, and Bradley (1998) measured the size and location of notches in the presence of positive and negative blur through dilated pupils for three subjects. They then simulated the MTF using diffraction-limited optics with and without the aberrations of the eye for each subject. The size and location of notches varied in individuals and they found that including the individual aberrations improved the prediction of the location of the notches. Their method for predicting the CSF in the presence of blur was improved by Strang, Atchison, and Woods (1999). Recently Guo, Atchison, and Birt (2008) investigated the effect of correcting the higher-order aberrations on the defocused CSF using adaptive optics (AO). Peak sensitivity increased when aberrations were corrected and notches were more symmetrically distributed around these maxima. Notch depth increased when compared with measurements without AO correction.

Notches that occur only for gratings of certain orientations have been shown to be produced as a result of neural factors, in patients with Multiple Sclerosis (Regan, Whitlock, Murray, & Beverley, 1980) and Parkinson’s disease (Regan & Maxner, 1987). Such orientation-specific notches were also attributed to optical factors by Apkarian, Tijssen, Spekreijse, and Regan (1987). They manipulated the size and location of notches in the CSF by varying cylindrical correction and grating orientation and found that inducing cylindrical blur of +0.50DC...
produced orientation-specific notches in the CSF. Analogous but smaller asymmetric blur is produced by the higher-order aberrations when the pupil is larger than 2.8 mm (Campbell & Gubisch, 1966). Recent work examining contrast sensitivity (CS) measured through small (3 mm) and large (>6 mm) pupils has shown that higher-order aberrations can cause orientation-selective reductions in grating-based CS for both normal eyes (Tahir et al., 2008) and those that have undergone refractive surgery (Murray et al., 2008; Tahir, Parry, Brahma, Ikram, & Murray, 2009). While most studies investigating the impact of the aberrations on the defocused CSF have largely ignored orientation as a variable, Atchison and Scott (2002) found changes between the defocused CSF for two orientations in one subject. They found these shifts to be influenced by the Stiles-Crawford effect (SCE) and in a further study Atchison, Marcos, and Scott (2003) investigated the influence of shifting the SCE-peak position on visual performance including grating based contrast sensitivity of two different orientations. However, the possible influence of the asymmetries present within the higher-order aberrations on the defocused CSF for different orientations has not been investigated.

**Theoretical considerations**

Figure 2 demonstrates how 0.25 \( \mu m \) of different Zernike terms for a defocused MTF contributes to the production of notches when orientation is varied. In the presence of \(-1DS\) of blur, spherical aberration produces notches of exactly the same size and location for both orientations. This is expected, as the blur will have circular symmetry. However, when the same amount of blur is added for the terms coma and trefoil, the effects become orientation specific, with one orientation affected substantially more than the others. The effect of horizontal coma is to induce notches when measured with a vertical grating while producing no such effect when measured with a horizontal grating. Trefoil on x-axis produces notches in the same location for both orientations, but these notches are of much larger amplitude for the vertical grating. Though not

Figure 1. Modulation transfer functions (MTF) for a model eye (6 mm pupil) with no blur (circle symbols), +1DS blur (square symbols) and −1DS blur (triangle symbols). Top graph (a) shows simulations when no aberrations are present and bottom graph (b) shows simulations with aberrations. Local minima, or notches, are evident when blur is added and these change in depth and location in presence of aberrations. Note square and triangle symbols are superimposed on graph (a) as equal reduction in MTF for both types of blur.

Figure 2. Effect of 0.25 \( \mu m \) of spherical aberration (a), horizontal coma (b) and trefoil on x-axis (c) on the modulation transfer function (MTF) for two orientations of grating, vertical (circles) and horizontal (crosses) in the presence of −1DS of blur. Note that spherical aberration produces the same reduction in MTF for both orientations whereas this is not the case for coma and trefoil. Pupil size was 6 mm.
illustrated here, simulated MTFs show that trefoil on y-axis and vertical coma produce different orientation effects. Vertical coma produces notches for a horizontal and not a vertical grating while trefoil on y-axis produces larger notches for a horizontal than a vertical grating.

The typical wavefront aberration of an eye will contain a mix of such aberration terms and so the addition of spherical blur should produce orientation specific effects. Whether these effects induce a measurable change in the CSF will depend on the amount of such aberration present. These will be dependent on the specific wavefront aberrations and so should vary between subjects. They will be predictable by computing the MTF for a diffraction-limited pupil provided individuals’ aberrations are included in the calculations.

One reason that orientation specific effects of the aberrations have not been considered previously is that compared to the uncorrected astigmatism measured by Apkarian et al. (1987), the size of aberration such as coma and trefoil is quite small. While the theory predicts that 0.25 μm of aberration in a single term should produce a notch of approximately 0.5 log unit, the asymmetric effect of the mix of aberrations present in real eyes may not be large enough to induce a measurable orientation-specific change in the CSF.

In order to investigate this we studied the interaction between defocus and aberrations at different orientations of sine-wave gratings and compared theoretical predictions with measured data. The main aim of the experiments was to determine the importance of grating orientation when measuring the defocused CSF.

### General methods

#### Contrast sensitivity measurements

CS for a range of spatial frequencies of sine wave gratings was tested for both vertical and horizontal gratings. Grating patterns were generated on a computer monitor (Sony GDM-f500) using a VSG (Cambridge Research Systems, Rochester UK) graphics card driven by purpose-designed software. The subject sat at a distance of 350 cm from the monitor. Alignment was maintained using a chin and forehead rest. The gratings were presented as circular Gabor patches of SD 0.75° and had a half height of 1.75°. The frame rate of the monitor was 120 Hz. The monitor was calibrated in terms of luminance and chromatic contrast using a PR650 spectrophotometer (PhotoResearch Systems Inc., Chatsworth, CA, USA) according to the method described in detail in Parry, McKeefry, and Murray (2006).

Initially measurements were conducted using a broadband polychromatic source (dominant wavelength 625 nm) with chromaticity x = 0.31 and y = 0.316 and mean screen luminance 12.5 cd/m². Pupils were dilated with 1% Tropicamide instilled 30 minutes prior to measurements being made and every hour thereafter. Subjects were refracted for the dilated pupil size. Refraction was corrected using lenses placed in a trial frame (HJT (right eye) −1.00/−0.75 × 165, REB (left eye) +0.50/−0.50 × 160, SIMR (right eye) −0.25/−0.25 × 110). The subject’s head was stabilized using a chin rest and brow bar. The maximum pupil size was used in the CS measurements (HJT 7.5 mm, REB 7.4 mm and SIMR 7.5 mm). For all subjects CS was measured both with the optimum refraction and with the addition of +1DS blur for 9 spatial frequencies (0.5, 1, 2, 4, 6, 8, 10, 12 and 14 c/deg).

In a second set of experiments, the source was changed to monochromatic and was viewed through a narrow band filter (538 nm with full-width at half height of 20 nm). Mean screen luminance was 13 cd/m². Pupils were dilated with 1% Cyclopentolate instilled 45 minutes prior to the measurements being made and every hour thereafter. Subjects were refracted after cycloplegia (HJT (left eye) −1.00/−0.50 × 10 and TP (left eye) +0.50/−0.50 × 175). The target was viewed through a 6 mm diameter artificial pupil placed as close to the subject’s eye as possible (both subject’s pupils dilated to greater than 7 mm). Again, the subject’s head was stabilized using a chin rest and brow bar. In this experiment the defocus measurements were made with −1DS blur added to the optimum refraction and 14 spatial frequencies were tested (0.5, 1, 2, 4, 5, 6, 9, 8, 9, 10, 12, 13, and 14 c/deg).

Tested eyes had better than 6/6 VA and all subjects were experienced in psychophysical testing. To ensure correct refraction a through focus measurement was also taken after normal refraction. This entailed measuring the CS at the two orientations (90° and 180°) for a 12 c/deg sine wave grating with the refraction in place. The contrast sensitivity was re-measured after changing the refraction in steps of ±0.12, ±0.25 and ±0.50DS. The refraction with which the CS for each orientation was highest was then used for that particular run.

Contrast (C) was defined after Michelson:

\[
C = \frac{L_{\text{max}} - L_{\text{min}}}{L_{\text{max}} + L_{\text{min}}},
\]

where \(L_{\text{max}}\) is maximum luminance and \(L_{\text{min}}\) is minimum luminance.

CS was measured in decibels (dB) where:

\[
dB = 20\log \left( \frac{1}{C} \right).
\]
changed and the endpoint was established when the step size was reduced to a single dB of contrast. Each orientation was tested 3 times and the mean of these was taken as the threshold. All subjects were experienced in psychophysical testing.

**Higher-order aberrations**

Aberrations were measured using an IRX3 (Imagine Eyes, Paris) commercially available aberrometer. It operates on the Hartmann-Shack principal and has a 32 × 32 lenslet array covering a maximum sample area of 7.2 × 7.2 mm², allowing for a spatial resolution of 230 μm on the pupil plane. The He-Ne laser has a wavelength of 780 nm. All aberrations were in Optical Society of America (OSA) format (Thibos, Applegate, Schwiegerling, & Webb, 2002). Subject’s aberrations were measured for the fully dilated eye, where:

Subject's aberrations were measured for the fully dilated eye, just prior to the CS measurements being conducted. The spectral sensitivity of the eye was taken as the threshold. All subjects were experienced in psychophysical testing.

**Optical modeling**

The optical modeling was incorporated in a Matlab (Version 7.4, The Mathworks Inc.) routine written by one of the authors. The model assumes a reduced schematic eye with refracting power of 60D and refractive index of 1.32. The SCE (Stiles & Crawford, 1933) reduces the effective pupil diameter, \( D_{\text{eff}} \), as the pupil enlarges in size. As this will have an impact on the visual effects of the aberrations in a large pupil, the SCE was incorporated as a Gaussian apodizing filter in the pupil function using:

\[
D_{\text{eff}} = \exp[-(\rho/2(r^2))]
\]

(3)

where \( r \) is the pupil radius at which the aberrations were measured and \( \rho \), which varies within the general population, was given the value of 0.12 (as found by Applegate and Lakshminarayan (1993) to be the mean population value).

Using a set of Zernike coefficients a pupil function, \( f(x, y) \), for a particular wavefront aberration \( W \) is calculated, where:

\[
f(x,y) = D_{\text{eff}}(\exp[-i2\pi W(x,y)]).
\]

(4)

The squared modulus of Fourier transform of the pupil function determines the point spread function (PSF) for the particular set of aberrations. The polychromatic MTFs were derived from their monochromatic counterparts by calculating the polychromatic PSF as the weighted sum of the monochromatic PSFs at various wavelengths (495 nm to 695 nm in 30 nm steps). The spectral sensitivity of the eye, \( V(\lambda) \), was used as a weighting function while the longitudinal chromatic aberration (LCA) of the eye, \( d\lambda \), was used to calculate the defocus at the various wavelengths (Thibos, Ye, Zhang, & Bradley, 1992). The LCA calculation was weighted relative to the dominant wavelength, but not the complete spectral output, of the monitor.

\[
PSF_{\text{pol}} = \int V(\lambda)PSF(x, y, \lambda) d\lambda.
\]

(5)

By taking the Fourier transform of the PSF the optical transfer function (OTF) was determined and the modulus of this gave the MTF.

The MTF of the eye was calculated using the average of four wavefront aberration measurements. The pupil size used for the aberrations was matched with that used for the CS measurements for each individual and measurement run. MTFs were calculated with blur (MTF\text{focused}) and without blur (MTF\text{defocused}). To predict defocused CS (CS\text{pred}) from the MTF the following equation (Atchison et al., 1998; Radhakrishnan, Pardhan, Calver, & O’Leary, 2004) was used:

\[
CS_{\text{pred}} = CS_{\text{focused}} \times \left| \frac{MTF_{\text{defocused}}}{MTF_{\text{focused}}} \right|.
\]

(6)

Following Atchison et al. (1998) and Strang et al. (1999) we have quantified the quality of the CS predictions by calculating the root-mean-square error (RMSE) using the following equation:

\[
RMSE = \sqrt{\frac{\sum (CS_{\text{defocused}} - CS_{\text{pred}})^2}{n-1}},
\]

(7)

where \( n \) was the number of spatial frequencies tested and \( CS_{\text{defocused}} \) is the measured defocused CS.

While the RMSE value itself is useful, it should be used in conjunction with a consideration of how the shape, in particular the location and depth of any notches, of the measured and predicted CS functions match. Atchison et al. (1998) reported the RMSEs of two repeated CS measurements with −2DS defocus of two subjects to be 2.8 dB and 3 dB while Strang et al. (1999) found values ranging between 2.4 dB and 8.8 dB when comparing the measured and predicted contrast sensitivity with ±2DS defocus.

**Results**

The aberration measurements for the four subjects are shown in Figure 3, using 1% Tropicamide (open bars) and 1% Cyclopentolate (closed bars). The initial experiment was conducted using Tropicamide for dilation and subjects HJT,
REB and SIMR. While these subjects have similar overall aberrations, with RMSE between 0.48 to 0.54 μm, the composition of the aberrations vary. As such it may be expected that notches will also vary between these three subjects. Figure 4 shows the measured CSF for the two grating orientations for the three observers. Also shown are the comparisons of the measured data with that predicted using the optical model incorporating each subjects’ individual aberrations. Most, but not all, defocused CSFs contain notches. There are variations in notch location and size between observers and also variations between the different orientations for the same subject. For HJT there is approximately equal reduction in CS with the blur for both orientations, but there is a notch present at 12 c/deg in the defocused CSF for the vertical grating which is not present for the horizontal. The measured CSFs match well with those predicted both in terms of shape of the CSF and the RMSE (1.88 dB for the vertical and 3.77 dB for the horizontal grating). For subjects REB and SIMR, the measured defocused CS shows clear differences between the two orientations. REB displays greater loss in sensitivity for the vertical than the horizontal grating at the higher spatial frequencies (6 c/deg and above) and also has dips in both orientations of the measured CSFs. These dips occur at different spatial frequencies (4 c/deg for the vertical grating and 6 c/deg for the horizontal grating). SIMR displays greater loss in sensitivity for the horizontal grating at the higher spatial frequencies (6 c/deg and above) while also showing a dip in sensitivity at 6 c/deg for the vertical grating, although this is not replicated in the predicted CSF. The predicted and measured data match well for both subjects in terms of overall RMSE (RMSE of 0.65 dB and 4.44 dB for REB and 0.35 dB and 2.67 dB for SIMR for vertical and horizontal gratings respectively), however there are notches seen in the measured data that are not replicated in the predictions. See Discussion.

Two subjects undertook additional measurements with blur of the opposite sign, −1DS. For a diffraction-limited aberration free system, equal power of defocus with opposite sign will have the same impact (see Figure 1a). This is not the case in an aberrated system however, as the aberrations will interact with the defocus (see Figure 1b for an example). This interaction will be dependent on the sign of defocus and the mix of aberrations (Woods, Bradley, & Atchison, 1996). For this experiment 1% Cyclopentolate was used to dilate the pupil and paralyze accommodation. Other changes to the experiment were introduced to improve the accuracy of the measured and predicted contrast sensitivity. The target was monochromatic to provide some insight into the role of transverse and longitudinal chromatic aberration. It was viewed through a fixed pupil of 6 mm to remove any potential error induced by fluctuating pupil size during the experiment. More spatial frequencies were sampled, as previous studies (Atchison & Scott, 2002; Atchison et al., 1998; Strange et al., 1999) have illustrated the advantages of high sampling rates.

From Figure 5 it can be seen that for both subjects the addition of blur produces different effects on the two orientations of gratings. The defocused CSF for the vertical grating of subject HJT shows more undulations than the horizontal, with a notch present at 11 c/deg. These differences are also reflected in the predicted CSF, where the shape of the curves follow similar, but exaggerated (by approximately a factor of 2), undulations. These exaggerations are particularly evident for the vertical grating CSF. The RMSEs are 3.6 dB and 2.8 dB for the vertical and horizontal orientations respectively. The data for subject TP again highlight differences in the two orientations when blur is added, as the vertical gratings display greater loss in CS than the horizontal, with a notch present for the vertical grating at 9 c/deg. These differences are present in the predicted data, where
the shapes of the predicted and measured curves match well for both orientations (RMSE 2.44 dB for vertical and 0.87 dB for horizontal grating data).

Having established the correspondence between the predicted and measured CSF, the MTF can be replicated to determine how the effects vary across a larger range of orientations. Figure 6 (a, b and c) illustrates the effect of equal but opposite blur (−1DS, top graphs, +1DS, lower graphs) for four different orientations of gratings (left to right, 180°, 90°, 45° and 135°). Note that aberrations used for these calculations were from the pupils dilated with 1% Tropicamide and the pupil sizes used were as stated in Figure 3.

The MTFs, which were calculated for polychromatic conditions, show variations in notch location and size between subjects and also between the different orientations for the same subject. For the negative defocus (top graphs), HJT has a notch present at 135° and two notches at 180° but no notches for the other two orientations. Notches are present with positive defocus, albeit with reduced size and number, but in the opposite orientations to that when negative defocus was added. While the negative blur produced notches at 135°...
and 180°, the positive blur produced notches at 90° and 45°. Subjects REB and SIMR have notches present at all orientations with negative defocus and these vary considerably in number and size. The modeling highlights the effects of positive and negative defocus. On average, positive defocus (lower graphs) produces fewer notches in the MTF than negative defocus (top graphs). Indeed, for subjects REB and SIMR the notches that are present with negative defocus are no longer present when positive defocus is added. This difference must be due to the interaction between the aberrations, principally primary spherical aberration, and defocus.

To demonstrate this the spherical aberration term was manipulated to produce new MTFs. The data, shown in Figure 7, are calculated for +1DS blur and a horizontal grating. [Note that there are no notches for these conditions, as shown in Figure 6, left column]. Either primary spherical aberration has been removed (solid line) or the sign (+) of the spherical aberration reversed (dashed line). All subjects display notches when spherical aberration is removed. They also have a greater loss in their MTF without spherical aberration. Reversing the sign of spherical aberration reduces the overall loss in the MTF, but increases the depth of the notches for all observers. The notches also shift to higher spatial frequencies when spherical aberration is added. The difference between the MTFs for reversed compared with no spherical aberration was smallest for HJT and largest for SIMR. This observation corresponds to the relative size of the primary spherical aberration term for these observers (as shown in Figure 3). Interestingly, the highest MTF without notches is produced by the natural aberrations of the eye, as can be seen by comparing the data in the left column of Figure 6 with that shown in Figure 7.

The data highlight the fact that differences between observers are a reflection of the mix of their aberrations. The implications are discussed below.

**Discussion**

We have shown through theoretical modeling that certain aberration terms, such as coma and trefoil, produce orientation specific notches in the MTF of a defocused...
optical system (as shown in Figure 2). These aberrations alter the CSF in an orientation-dependent manner. The main aim of this study was to establish whether these effects are measurable and to determine if orientation is a significant factor when investigating the effects of aberrations. It is clear that orientation-specific changes were demonstrated in the defocused CSF when measured through a dilated pupil and these were found to match well with predictions based on the subjects’ aberrations. This was also well predicted by the optical modeling, again confirming that the aberrations must be responsible for the orientation-specific changes.

Variations between individuals in notches that are produced in a defocused CSF have been linked to the
aberrations of the eye in previous studies. As mentioned in the introduction, orientation-specific changes in the CSF have been seen as a result of neurological disease (Bodis-Wollner & Diamond, 1976; Regan et al., 1977) or induced cylindrical defocus of at least +0.50DC (Apkarian et al., 1987). Atchison and Scott (2002) and Atchison et al. (2003) linked orientation specific changes in the defocused CSF with alterations in the SCE peak position. This is the first study to demonstrate that the aberrations of the eye alone can produce orientation specific changes in the defocused CSF.

The predictive ability of the theoretical model used in this study was generally good but with some discrepancies. In general, and particularly for high spatial frequencies, the performance of the eye is superior to that predicted by the modeling. The RMSE of the measured versus predicted contrast sensitivity was similar to that found by other studies (Atchison et al., 1998; Strang et al., 1999), although they used defocus of 2DS while we used 1DS. Notches of greater size were seen in the predicted than the measured data, which contained smaller undulations or dips in the CSF. This is a feature also seen in previous studies. The size of the dips in the CSF and reduction in CS induced by the blur in the current study is comparable to that found by Woods et al. (1996) who also used ±1DS defocus in their measurements. Guo et al. (2008) used monochromatic light and fine spatial frequency sampling to measure larger notches (nearly 20 dB in some cases) using the same amount of blur, but again found that in some instances the predicted loss was greater than that measured.

Some of the differences seen between the measured and predicted data may be due to the aberration data used to generate the predicted data. Dynamic changes in the aberrations of the eye due to tear film layer changes and eye movements cannot be captured effectively by taking a snapshot of the aberrations. Temporal instability of the higher-order aberrations in the form of micro fluctuations in the RMS of the various Zernike modes has been shown in both cyclopleged and non-cyclopleged eyes and at both near and far targets (Hofer, Artal, Singer, Aragon, & Williams, 2001). These dynamic shifts in the aberrations will produce discrepancies between the measured and predicted CSFs, the latter of which were based on static measurements of higher-order aberrations. Evidently these fluctuations cannot be fully incorporated in the modeling by averaging four measurements of the aberrations as was done here. Ideally the aberrations would be measured simultaneously with the contrast sensitivity measurements to account for these changes.

The modeling assumed that the eye’s 2nd order Zernike modes of spherical defocus and astigmatism were fully corrected from the refraction, yet even with the careful refraction conducted some residual error will have been present. Thibos, Hong, Bradley, and Cheng (2002) measured the residual aberrations in the optimally refracted eye and found that most retained residual negative (hyperopic) spherical defocus and to a lesser extent with-the-rule astigmatism. They hypothesized that the residual refraction may counterbalance the higher-order aberrations to improve visual performance. As the model did not include this residual refraction this may explain why dips in CS were seen in the measured but not the predicted CSF for subjects REB and SIMR and the inclusion of the residual refraction would have improved the accuracy of the predicted MTF. Another limitation of the polychromatic modeling was that the spectral output of the monitor was not taken into account in the model. However, the measured dips for these two subjects were also of small depth while the measured CS showed the greatest variability and so the error may be in the measurements as opposed to the predicted data. The data for HJT in the monochromatic conditions showed a greater loss in sensitivity in the predicted data than that measured and this may also be due to some of the factors mentioned above.

Another factor affecting the predictive power of the model could be the use of the average ρ factor of value 0.12 for modeling the SCE. Variations in this will change the effective pupil diameter and hence the predicted loss in sensitivity. To test for the impact of the SCE in our
model, the $\rho$ factor was varied between two extremes ($\pm 0.05$) and the resultant change found was of the order of 3–4 dB in the MTF. There is also some intersubject variability in the SCE peak position (Applegate & Lakshminarayanan, 1993; Marcos & Burns, 2000) and it has been shown that there is a slight but significant improvement in image quality when the SCE is centered on the subject’s true SCE peak position rather than the center of the pupil (Marcos & Burns, 2000). Atchison et al. (2003) found that peak position of the SCE had an effect on the defocused CSF and that the influence of shifting the SCE-peak position on grating CS is orientation specific. Shifts in the SCE peaks between subjects were not taken into account in our model. Variations in the SCE may, therefore, be a small factor in the discrepancies seen in the modeling in this study. Aside from these optical considerations, the superiority of the CS over the modeling for some subjects suggests that neural factors may also be at work.

Theoretical modeling predicted notches predominantly for negative (hyperopic) defocus for the three subjects, with positive (myopic) defocus producing notches in the MTF of only one subject, HJT. Woods et al. (1996) have shown that notches are most prominent when defocus and spherical aberration have the opposite signs. Our results also illustrate this, as shown in Figures 6 and 7. All subjects have positive spherical aberration (as shown in Figure 3) and this leads to an improvement in the MTF when positive, as opposed to negative, defocus is added. The highest MTF without notches is produced with the eye’s natural aberrations rather than with manipulated aberrations. This is in agreement with McLellan, Prieto, Marcos, and Burns (2006), who found that eyes’ aberrations are interdependent in ways that improve the MTF. However, an interesting effect was seen in subject HJT where blur of different direction produced entirely different orientation selective notches. For the horizontal grating, notches were produced when negative defocus was added but not for positive defocus while for the vertical grating the reverse was true. While all observers had positive primary spherical aberration (as shown in Figure 3), of the three observers used to produce the MTFs in Figure 6, HJT had the smallest amount of positive primary spherical aberration while the largest aberration term was both negative in value and asymmetrical (trefoil on y-axis). For this subject the interaction between the spherical and asymmetric aberration terms lead to these orientation-specific effects. Our results demonstrate that asymmetries in the aberrations will induce orientation specific notches within the defocused MTF.

The implications of the findings of the current study are demonstrated by examining the conclusions drawn by other studies in describing the variations seen in the MTF between positive and negative blur. Strang et al. (1999) predicted the MTF for 3 subjects and found that 2 subjects had more notches when negative blur was added while the reverse was true for the third. They attributed this to the greater amount of coma present in this subject’s aberrations compared with the others. As coma induces asymmetric blur, the notches produced in this subject’s MTF will be orientation-specific. There may have been orientation and defocus specific effects, such as those seen for subject HJT in this study. As the MTF will depend on the interaction between induced blur and orientation of gratings, reproducing their experiments at many orientations may minimize the differences between observers. Similar reasoning applies to the asymmetries between the positive and negative defocused CSF seen in Atchison et al. (1998) for one subject.

The third order Zernike aberrations, consisting of coma and trefoil, have a significant contribution to the variance of the wavefront in an individual eye (Howland & Howland, 1977; Porter, Guirao, Cox, & Williams, 2001; Walsh, Charman, & Howland, 1984). It is therefore important that orientation is taken into account when measuring grating-based contrast sensitivity.

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