Published in final edited form as:

Ophthalmic Physiol Opt. 2014 May ; 34(3): 309–320. doi:10.1111/opo.12114.

Influence of spherical aberration, stimulus spatial frequency, and pupil apodisation on subjective refractions

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Abstract

Purpose—To test competing hypotheses (Stiles Crawford pupil apodising or superior imaging of high spatial frequencies by the central pupil) for the pupil size independence of subjective refractions in the presence of primary spherical aberration.

Methods—Subjective refractions were obtained with a variety of test stimuli (high contrast letters, urban cityscape, high and low spatial frequency gratings) while modulating pupil diameter, levels of primary spherical aberration and pupil apodisation. Subjective refractions were also obtained with low-pass and high-pass stimuli and using “darker” and “sharper” subjective criteria.

Results—Subjective refractions for stimuli containing high spatial frequencies focus a near paraxial region of the pupil and are affected only slightly by level of Seidel spherical aberration, degree of pupil apodisation and pupil diameter, and generally focused a radius of about 1 to 1.5 mm from the pupil centre. Low spatial frequency refractions focus a marginal region of the pupil, and are significantly affected by level of spherical aberration, amount of pupil apodisation, and pupil size. Clinical refractions that employ the “darker” or “sharper” subjective criteria bias the patient to use lower or higher spatial frequencies respectively.

Conclusions—In the presence of significant levels of spherical aberration, the pupil size independence of subjective refractions occurs with or without Stiles Crawford apodisation for refractions that optimise high spatial frequency content in the image. If low spatial frequencies are optimised by a subjective refraction, spherical refractive error varies with spherical aberration, pupil size, and level of apodisation. As light levels drop from photopic to scotopic, therefore, we expect a shift from pupil size independent to pupil size dependent subjective refractions. Emphasising a “sharper” criterion during subjective refractions will improve image quality for high spatial frequencies and generate pupil size independent refractions.

Keywords

refractive error; spherical aberration; Stiles Crawford Effect; apodisation; spatial frequency; psychophysical criterion

Introduction

The unaccommodated human eye typically has significant levels of positive spherical aberration (SA)¹⁻⁶. Therefore, when refracting the eye through annular pupils of increasing radius, the eye appears more myopic^{7, 8}. Interestingly, no such myopic shift has been observed when refracting the eye with circular pupils of increasing radius⁷⁻¹². However, at scotopic light levels a myopic shift accompanied increasing pupil radius⁷. With the now routine control of SA levels on both intraocular lenses and contact lenses, sometimes adding negative SA¹³⁻¹⁷, sometimes removing SA^{13, 15, 18, 19}, and sometimes introducing large amounts of SA to achieve multifocality^{20, 21}, it is timely to examine the impact of SA manipulation on spherical refractions.

One hypothesis to explain the photopic pupil size independence of spherical refractions (Rx) and the myopic shift observed scotopically is the inherent central bias of photopic vision known as the Stiles Crawford Effect (SCE)²²⁻²⁴, which is almost absent at scotopic light levels²⁵. The hypothesis argues that the SCE will attenuate the visual impact of marginal rays resulting in reduced impact of the spherical aberration and other high order aberrations on Rx^{8, 9} for photopic vision but not at scotopic light levels where SCE is almost absent. However, in a spherically aberrated eye, modelling results from our group²⁶ and also Atchison^{27, 28} indicate that SCE should have very little, if any, impact on spherical refraction in spite of acting as a moderating influence on the effects of defocus^{28, 29}.

An alternative hypothesis argues that any high spatial frequency refraction will always be paraxially biased because the aberrated margins of the pupil are ineffective at imaging high spatial frequencies²⁶. Optically, it is as if spherical aberration induces a small paraxial aperture that, when well focused, can image high spatial frequencies. However, this induced aperture expands to fill the entire pupil when imaging low spatial frequencies²⁶, which explains the myopic shift observed with low spatial frequencies in the presence of positive SA^{7, 8, 27, 30, 31, 32, 33}. Therefore, the myopic shift that accompanies pupil dilation at scotopic light levels stems from the presence of positive SA and the drastically reduced visual bandwidth available at very low light levels^{7, 8, 34}. However, it is difficult to conclude from these prior studies if the myopic shift observed by Koomen⁷ at low light levels was due to SA and an absence of SCE or a shift in the neural bandwidth to lower spatial frequencies, because numerous other changes occur as we switch from photopic to scotopic vision, e.g. a shift to photoreceptors sensitive to shorter wavelengths and the shift of vision out of the rod-free foveola.

Therefore, to understand the impact of spherical aberration and both pupil apodisation and visual bandwidth on subjective refraction, we aimed to avoid the confounding variables associated with the changeover from photopic to scotopic vision by studying refraction under exclusively photopic conditions while independently controlling pupil apodisation and stimulus spatial frequency content.

Methods

Manipulation of the eye's pupil function

Subjects viewed a computer display through optical devices designed to independently control the optical phase and amplitude portions of the pupil function of the human eye. When including either phase or transmission control in the optical path, two important principles are employed. First, wavefront phases add. Therefore, we selected a phase plate with sufficient SA that, when added to the SA of each eye, generated the desired level of SA. Second, pupil transmissions multiply. To obtain a specific pupil transmission function, we selected a Gaussian filter that, when multiplied by the eye's SCE, produced the desired level of central or marginal bias. Before the experiment, levels of SA (C_4^0 in μm) present in each eye were measured by the COAS aberrometer (<http://wfsci.com>)³⁵ and the SCE was determined by measuring the relative luminous efficiency profile for 550nm monochromatic light entering different parts of mid-horizontal plane of the subject's entrance pupil²³.

Using computer controlled lathes, 25 phase plates were made from 12 mm diameter and 4 mm thick PMMA blanks with a plane back surface and a lathed front surface. Phase plates were axially afocal with C_4^0 levels ranging from -0.6 to $+0.6 \mu\text{m}$ in $0.05 \mu\text{m}$ increments (6 mm pupil diameter values). To make these phase plates axially afocal, a defocus term (Z_2^0) was added to the Zernike primary SA (Z_4^0) with a coefficient $C_2^0 = \sqrt{15} \times C_4^0$ ³⁶. Phase plates were calibrated by the fabrication lab (College of Optometry, University of Houston) and again at Indiana University School of Optometry using a Wavefront Sciences Clear Wave single pass Shack-Hartmann aberrometer (<http://wfsci.com>), and mean errors for C_2^0 and C_4^0 were 3.7% and 3.1% of their respective target values. By viewing through these axially afocal waveplates, we introduce controlled levels of Seidel, not Zernike, SA²⁶³⁶.

Pupil transmission characteristics were controlled with photographically generated Gaussian spatial filters using the methods described by Rynders²³ and Atchison²⁴. Photographic processing non-linearities were corrected, and filter transmission characteristics were confirmed with a photometer (www.photoresearch.com). In combination with the SCE of the average eye, the Gaussian filters provided effective sigmas of approximately -0.115 (reverse SCE), 0 (uniform pupil), $+0.115$ (normal SCE), and $+0.230$ (double SCE) mm^{-2} where transmission (T_r) varied as a function of radius (r) in mm

$$T_r = e^{-\sigma \cdot r^2} \quad \text{Equation (1)}$$

Total transmission through each filter was computed as a function of pupil diameter to determine the spatially homogeneous neutral density filters required to combine with the Gaussian filters to provide a constant retinal illuminance for all test conditions. Total Transmission (T%) as percentage of the unfiltered pupil can be calculated as:

$$T\% = 100 \cdot \frac{\frac{\pi}{\sigma} (1 - e^{-\sigma R^2})}{\pi R^2} = 100 \cdot \frac{1 - e^{-\sigma R^2}}{\sigma R^2} \quad \text{Equation (2)}$$

where R is the semi-diameter of the pupil.

As sigma increased, the total transmission decreased, and therefore to maintain a fixed effective target luminance, neutral density filters were combined with the apodising filters. A computer controlled digital display was rear projected onto a screen and viewed through a unit magnification telescope³⁶. All optical components, the subjects' pupil centres and the stimulus centre shared a common axis. A plane located one focal length in front of the first telescope lens was conjugated with the subject's pupil plane. The front surfaces of the SA phase plates were located in this plane, as were the apodising filters and artificial pupils. Approximately 1.5 cm anterior to this plane, the spherical lens wheel in a modified phoropter head was used to vary target vergence in a plane similar to that used in a clinical refraction. Phase plates, apodising filters, and artificial pupils were all aligned and maintained coaxial with the subject's primary line of sight using a bite bar and video monitoring throughout the experiment. The stimulus display was positioned 2.88 meters from the pupil conjugate plane.

Visual stimuli

Maximum luminance of the rear projection display stimulus was 10,000 cd/m². Effective display luminance of our whole system was determined by absorption and reflections from all of the intervening optics and the combined Gaussian and neutral density filters, resulting in test stimuli with a white (maximum) luminance of 72 cd/m². Display nonlinearities were compensated for by pre-distorting the test stimuli.

Unlike most studies of refraction, we employed a wide range of visual targets to manipulate the spatial frequency spectrum of the stimulus (Figure 1). In experiment 1, refractions were obtained with three lines of five letters each from a high contrast letter chart (logMAR 0.18 – 0.35, Snellen fraction 6/9 – 6/13 or 20/30 to 20/45), 3 degree diameter Gaussian weighted patches of low spatial frequency (SF) (1.8 cpd, contrast 0.54) and high spatial frequency (15.5 cpd, contrast 0.2) gratings, and a 4.8 × 3.6 degree image (720 × 540 pixels) of a modern cityscape in color (left side of Figure 1). In experiment 2, unfiltered and filtered versions of an older building (4.8 × 3.6 degrees, 720 × 540 pixels), and a letter E (0.40 logMAR, Snellen fraction 6/15 or 20/50) were used (right side of Figure 1). The Gaussian low-pass filter used to blur the church image had a transmission of 10% at 9.5 cpd. The 0.40 logMAR letter was low and high pass Gaussian filtered with transmissions of 10% and 90%, respectively, at 2.5 cycles per letter. A rectangular high-pass filter with a cut-off of 3.25 cycles per letter was also applied to the 0.40 logMAR letter.

Control of accommodation

A serious concern when running extended psychophysical studies of refraction is the unwanted impact of accommodation. This is often combated by employing a cycloplegic agent, which also acts as a mydriatic. However, the impact of cycloplegia is not stable³⁷⁻³⁹, particularly over periods exceeding one hour. To avoid the confounding influence of unwanted accommodation, we adopted a strategy of employing eyes lacking any accommodation by restricting subject age to those >55 years⁴⁰. We also used an aberrometer-based optometer to confirm that each subject had zero measurable objective accommodation. To achieve the long lasting pupil dilation effects needed for this study an initial drop of 2.5% Phenylephrine combined with 1% Tropicamide was used. During the

experiment, pupil size was checked and if it decreased to near 7 mm, extra single drops of Tropicamide were added. Two healthy male subjects participated in our experiment. The tested eye had clear optics and no ocular or systematic diseases. Distance Rx, obtained with a phoropter-based eye exam viewing small high contrast letters, for the tested eye of subject #1 (age 57) was the same for 7mm, 3mm and 1 mm pupils ($+0.87-0.50 \times 55$). Ocular C_4^0 was $+0.465 \mu\text{m}$ measured by COAS for 7 pupil diameter and his Stiles Crawford function was fit with a Gaussian, $\sigma=0.133 \text{ mm}^{-2}$. Distance Rx for subject #2 (age 64) was the same for both 7mm, 3mm and 1 mm pupils ($-0.12-1.25 \times 75$) and $C_4^0 = +0.466 \mu\text{m}$, and his SCE was fit with $\sigma = 0.124 \text{ mm}^{-2}$. The elevated levels of SA in these two eyes are typical for this age range⁴¹⁻⁴⁴ and the pupil weightings are also typical⁴⁵. Most of the data shown in the Figures come from subject #1, but all experiments generated similar data for subject #2.

Psychophysical methods

Rx was determined using a forced-choice subjective refraction staircase method. Subjective cylinder refractions were included in the phoropter head during all spherical refractions. For each condition, five refractions were performed using a staircase that started with a lens in the phoropter chosen to differ from best focus pseudo-randomly in magnitude and sign (each trial began by “spinning” the phoropter wheel controlling the sphere power). The experimenter was unaware of the magnitude of this error, and could not view the phoropter controls during each refraction, enabling the experiment to achieve effective double masking. The subject was unaware of the optical conditions being tested or the starting point of each refraction staircase, and the experimenter controlling the phoropter was unaware of the final refraction until the staircase was completed. Each refraction staircase started with choices differing in 0.50 dioptre steps. After the first reversal, step size was reduced to 0.25 D, and after the 2nd reversal, step size was reduced to 1/8th dioptre (the smallest steps were not used with the low spatial frequency stimulus due to increased depth of focus). Subjects chose the subjectively “most focussed” or conversely “least blurred” of two lens options (“one or two”). The next pair included the chosen lens from the previous pair and a new lens one increment (0.50, 0.25, or 0.125 D) from the previous lens. In this way, lenses that produced a better subjective focus were sequentially selected. Rx was determined by the final chosen lens power after the second reversal with the 1/8th dioptre lenses. The induced change in subjective Rx for each trial was the final chosen lens power plus the individual phase plate's small amount (mean 0.05 dioptres) of paraxial power minus the subject's paraxial Rx.

During experiment 1, subjects were not provided explicit instructions for the criteria they should employ to identify the lens that provided subjective “best focus” for letters and pictures. With the grating stimuli, subjects identified the lens that maximised perceived contrast. In experiment 2, subjects were instructed to use specific criteria when viewing the unfiltered E: the lens that produced the “greatest perceived contrast”, or the “sharpest edges”. Experimental protocols were approved by the Indiana University institutional review board, adhered to the tenets of the Declaration of Helsinki, and required informed consent from each subject.

Theoretical model for predicting refraction of the aberrated eye

In a model eye with only SA, it is straightforward to quantify the significant impact of SA level on paraxial Rx, minRMS Rx (refraction that minimises the wavefront RMS), and marginal Rx. The difference between a paraxial Rx and a minRMS Rx (same as the difference between the minRMS Rx and marginal Rx) is

$$\Delta Rx \text{ (Diopters)} = \text{paraxial Rx} - \text{min RMS Rx} = C_4^0 \bullet \frac{\sqrt{5} \bullet 2 \bullet 6}{R_{max}^2}.$$

For example, the difference between a refraction that minimises the wavefront RMS (minRMS Rx) and one that focuses the pupil centre (paraxial Rx) will be 6.7, 4.3, 3.0, 2.2, and 1.7 dioptres per μm of C_4^0 for 4, 5, 6, 7, and 8 mm pupil diameters, respectively, and the difference between paraxial and marginal refractive errors are double these values²⁶.

Because each SA phase plate was axially afocal, we chose to establish the axial Rx (paraxial Rx) as our reference, which never changed during the experiment, and thus all Rx values reported are relative to the paraxial Rx. Paraxial Rx was established experimentally as the small pupil subjective refractions (pre-experiment subjective Rx obtained with small high contrast letters was the same for 1 mm and 3 mm pupils).

To interpret the results of our experiments, it is helpful to have available a method for inferring which part of the eye's pupil dominated the final determination of refractive error. We did this by computing the radial distance in the pupil that is focussed when the subject indicates the retinal image as a whole appears focused. The vergence profile of Z_4^0 can be used to define the refraction at each pupil radius, where $V(r)$ is the vergence relative to the paraxial power:

$$Rx = -V(r) = -C_4^0 \bullet \frac{\sqrt{5} \bullet 6 \bullet 4 \bullet r^2}{R_{max}^4} \quad \text{Equation (3)}$$

and therefore by substituting RiF (radius in focus) for r , the radius in focus can be quantified from the slope of the function relating Rx to C_4^0 , and thus inferred from the experimental data shown in Figure 2 using equation 4.

$$RiF = \sqrt{\frac{(-Rx/C_4^0) \bullet R_{max}^4}{24 \bullet \sqrt{5}}} \quad \text{Equation (4)}$$

Results

In the first experiment, we monitored the impact of SA sign and level on subjective Rx for four different pupil transmission functions (Figure 2): uniform (A: SCE=0), normal (B: SCE=1), reverse (C: SCE=-1), and double (D: SCE=2). Pupil diameter was 7mm. Subjective refractions for the VA chart, cityscape, and patch of high spatial frequency grating were almost identical. Although remaining close to paraxial Rx for each pupil transmission function, they become slightly myopic in the presence of +SA, and hyperopic with -SA. Both high spatial frequency Rx and low spatial frequency Rx vary linearly with level and sign of SA (for example, with normal SCE slope = $-0.36 \text{ D}/\mu\text{m}$ (high SF Rx) and $-1.97 \text{ D}/\mu\text{m}$ (low SF Rx) for subject #1; and $-1.1 \text{ D}/\mu\text{m}$ (high SF Rx) and $-2.15 \text{ D}/\mu\text{m}$ (low

SF Rx) for subject 2), and in the presence of typically levels of C_4^0 (e.g. $+0.4 \mu$ for a 7 mm pupil) high spatial frequency refractions differ by only about 0.2 D from the paraxial reference. Subjective refractions for the low spatial frequency grating stimulus were significantly affected by SA, paralleling the effect of SA on the minRMS refractions (Figure 2). The similarity of the subjective refractions observed with high contrast letters and a well focussed cityscape with the subjective refraction that maximised high spatial frequency modulation emphasises that subjective refractions with typical spatially broad-band stimuli will maximise the high spatial frequency modulation within these images irrespective of level of pupil apodisation.

As pupil apodisation increases, the effects of SA on Rx are generally reduced, which can be seen by the reduced slope of the data functions in Figure 2. The impact of pupil weighting function is shown directly in Figure 3 where we plot Rx vs. SCE weighting factor from reverse apodisation (SCE = -1) through to double apodisation (SCE = 2) with high levels of + and - C_4^0 ($+0.9 \mu$, Figure 3A, or -0.8μ , Figure 3B). Notice that with positive SA, when pupil weighting shifts from a highly central (double apodisation) to marginal (reversed apodisation) bias, Rx becomes more myopic for all test stimuli. Conversely, with negative SA, shifting pupil transmission bias to the pupil margins introduces hyperopia for all stimuli. Even in the presence of these high levels of SA, refractions for stimuli containing high SFs remain close to (within 0.25 D of) paraxial Rx with the most centrally biased pupil function. As bias shifted toward the margin, Rx shifted by about 0.25D with -SA and 0.5 D with +SA. Of note, with a 7 mm pupil and $+0.9 \mu$ of +SA, the marginal refraction would be -4.00 D and the min RMS refraction -2.00D. Refractions for the low spatial frequency gratings in the presence of +SA are much more myopic or hyperopic with -SA⁴⁶. Also, pupil weighting has a much larger impact on low spatial frequency refractions than we observed with high spatial frequencies.

These results clearly show a central pupil bias for subjective refractions even in the absence of pupil apodisation, but this central bias disappears when refractions are based upon low spatial frequencies. These data, therefore, fail to support the pupil apodisation hypothesis for the pupil size independence of photopic subjective refractions. As predicted by the aberration-induced effective aperture hypothesis²⁶, SA generates refractions with a central pupil bias in the absence of apodisation for high spatial frequency content stimuli that disappears when refractions employ low spatial frequency stimuli.

Control for chromatic and higher-order aberrations

The human eye has both chromatic aberration⁴⁷ and a full suite of higher order monochromatic aberrations⁴⁸. In order to examine the impact of these other aberrations, we directly compared the effect of C_4^0 on Rx observed subjectively with polychromatic stimuli to objective refractions calculated computationally with a monochromatic model containing only C_4^0 and C_2^0 ²⁶. The computational model calculated the Rx that maximised image modulation for a wide range of SFs, and we measured subjectively refractions at 1.8 and 15 cpd. The subjective refractions for the uniform pupil case are almost identical to the model predictions for both 7 mm and 4 mm pupils (Figure 4). The ability of the model to predict the behaviour of the real eye is evidence that these other aberrations have little influence on

the effect of spatial frequency on Rx in the presence of primary SA. Experimentally determined Rx matched the model predictions for all levels of pupil apodisation.

Pupil radius focused by subjective refractions

When subjective refractions focus the pupil centre, they should not change as we introduced different levels of Seidel SA, whereas subjective refractions that minimise wavefront RMS (as they do for low spatial frequency stimuli) should vary linearly with SA level with a negative slope of $-\frac{\sqrt{5} \cdot 6 \cdot 4 \cdot R_i F^2}{R_{max}^4}$.

We used regression analysis to identify the slopes of the data plots in Figure 2, from which we determined the radius in focus (Figure 5). The measured radius in focus value is important because it indicates which part of the pupil was optimally focussed during the refraction procedure. We found that for a 7mm pupil diameter and normal SCE, when subjects focused a VA chart, high spatial frequency grating, or cityscape, radius in focus for Subject One was around 1mm from the pupil centre, and for Subject Two close to 1.5mm away from the pupil centre. However, when focussing a low spatial frequency grating stimulus, radius in focus was approximately 2.5 mm from the pupil centre, which is close to the radius focused by a min RMS Rx (2.49mm). As central weighting increased (SCE=2), the high spatial frequency radius in focus decreased slightly. As central weighting was removed and replaced with marginal weighting, radius in focus increased, e.g. from 1.0 mm to 1.4 mm (subject 1, 7 mm pupil), and from 1.5 to 1.8 for Subject Two. A similar radius in focus (approximately 1 mm) was also determined for Subject One when viewing with a 4 mm diameter pupil.

If subjective refractions are being determined by a near paraxial region of the pupil (e.g. focusing a radius of 1-1.5 mm from the pupil centre), we would not expect any change in subjective refractions as pupil diameter was increased from 4 to 7 mm (see Figure 5 of Xu et al, ²⁶), whereas we expect that pupil size will affect subjective refractions that are determined more by the marginal optics (e.g. for low SF stimuli). We examine the impact of pupil size changes with and without apodisation and for both high and low SFs by comparing Rx for 4mm and 7mm pupil diameters (Figure 6). Total C_4^0 values (phase plate combined with eye) for the 7 mm pupils are $-0.8 \mu\text{m}$, $0 \mu\text{m}$ and $+0.9 \mu\text{m}$. For all subjective refractions based upon high SFs (letter chart, high SF grating, urban cityscape), the change in pupil size produced less than 0.15D of refraction change even in the presence of very high levels of SA. These modest changes are contrasted to the very significant changes that occurred when subjective refractions were obtained with low spatial frequency images and thus focused more marginal regions of the pupil. For example, with $+0.9$ and $-0.8 \mu\text{m}$ of primary SA, Rx changed by -1.46D and $+1.39\text{D}$, respectively, as pupil size was increased from 4 to 7 mm with a uniform pupil function, and these changes were reduced to -1.41D and $+0.78\text{D}$ with normal SCE.

Manipulating the spatial frequencies used during subjective refractions

In experiment 2 we examined the impact of spatial frequency by comparing the effect of altering the spatial frequency range used to perform a subjective refraction by either filtering the stimulus (Figure 1) or adjusting the subjective criterion. Using a 7 mm diameter pupil,

we show that SA has a much larger effect on Rx after removing the high spatial frequencies from a picture of a church (Figure 7A). In a similar experiment using a series of spatially filtered 20/50 letter Es (Figure 1), removing the high spatial frequencies amplified the effects of SA (Figure 7B&C). Also, when subjects employed either “sharper” or “darker” to judge best focus (Figure 7B&C), the subjective Rx's were almost identical to those obtained with the high pass filtered and low pass filtered Es, respectively. We interpret these results as evidence that these different subjective criteria represent a shift in the spatial frequency being used to select best focus.

Discussion

By controlling the level of pupil apodisation, we were able to confirm that the pupil size independence of spherical subjective Rx in the presence of SA is not due to the SCE. A near paraxial bias exists for refraction even in the absence of pupil apodisation. Subjective refractions of typical stimuli containing high spatial frequencies focus the high spatial frequency content within these stimuli. However, if subjects are forced to use low spatial frequencies, subjective refractions will focus a more marginal region of the pupil, and since SA and pupil size will change the marginal refractions, they will also change the low spatial frequency subjective refractions. Therefore, the myopic shift observed with pupil dilation at scotopic light levels⁷ is consistent with a shift to a low spatial frequency refraction due to the reduced neural bandwidth available at low light levels³⁴. This shift to a low spatial frequency refraction will make subjective refractions more sensitive to the removal of SCE (Figure 3, see also Atchison *et al*²⁷). In the end, the myopic shift observed by Koomen⁷ with pupil dilation at scotopic light levels likely reflects both a neural shift to low SFs, the presence of SA and not the absence of SCE, and as such we reject the SCE hypothesis for a central pupil bias in subjective refractions. Our data, as well as our modelling result²⁶, support the induced aperture model for this central pupil bias in the presence of SA.

Clinically, the ophthalmologists and optometrist often use the “darker” and “sharper” criteria to refine subjective refractions⁴⁹. Our experiments indicate this method forces the patient to choose between a contrast maximising lower spatial frequency refraction and a sharpness maximising high spatial frequency refraction²⁶. Because this refraction technique is typically employed in unaccommodated eyes, most of which have significant positive C_4^0 ^{1, 2, 50, 51} the “darker” refraction is usually more myopic than the hyperopic refraction. However, when we reversed the sign of SA, the darker refractions were more hyperopic (see Figure 8). Interpretation of the “darker” and “sharper” subjective criteria is more complicated in the case of a pre-presbyopic patient with active accommodation, when it is generally assumed that the perceived darkening (increased contrast) that accompanies introduction of minus lens power not needed to correct the Rx reflects accommodation, which in most eyes will lower the accommodative error and ocular spherical aberration and improve image quality⁵².

In our study we modulated SA levels using a series of axially afocal phase plates (see methods), but we quantified SA level using the familiar Zernike coefficient C_4^0 ⁵³. If pure Z_4^0 SA is added, there will be no change in the minRMS refraction, but a significant change in paraxial refraction (e.g. 2.2 dioptres of hyperopia per μm of +SA for the 7 mm pupils used

in this study). Because subjective refractions are paraxially biased, Seidel SA has little impact on typical subjective refractions (Figure 3). However, because Zernike SA alters paraxial power (because of the embedded r^2 term), adding or subtracting pure Zernike SA is expected to produce significant changes in subjective refractions^{36, 54-57}. For example, the anticipated hyperopic shift in refraction caused by the $-r^2$ term within positive Zernike

primary SA polynomial ($Z_4^0 = C_4^0 \cdot \sqrt{5} \cdot (6\rho^4 - 6\rho^3 + 1)$) will introduce a paraxial refractive error of 6.7, 4.3, 3.0, 2.2, and 1.7 dioptres per μm of C_4^0 for 4, 5, 6, 7, and 8 mm pupil diameters, respectively. Of course, if Seidel SA (instead of Zernike) is added (by cancelling $-r^2$ term in Z_4^0), paraxial refraction will not change, but the subjective (Figure 3) and objectively optimal²⁶ near-paraxial refractions will change slightly. For example, a drift to myopia with positive SA of -0.36 dioptres per μm of C_4^0 was observed in our study with a 7 mm pupil, and with a 6 mm pupil Yi et al⁵⁷ observed a slope of $2.9\text{D}/\mu\text{m}$ of added Z_4^0 or $-0.1\text{D}/\mu\text{m}$ relative to paraxial focus while Rocha et al⁵⁸ observed a $+2.6\text{D}/\mu\text{m}$ of added Z_4^0 , or $-0.4\text{D}/\mu\text{m}$ relative to paraxial focus. Thus, these two studies both indicate a near paraxial focus was achieved by subjective refractions in the presence of primary SA. By substituting their slopes (e.g., $-0.4\text{D}/\mu\text{m}$, $-0.1\text{D}/\mu\text{m}$ respectively) into our equation 4 we find a near paraxial radius in focus of 0.8mm and 0.4mm in the Rocha and Yi studies, respectively.

One of the most striking features of these refraction data is not related to the average results, but the refraction standard deviations, or precision. When designing this study, we (see methods) employed a refraction staircase that used steps of 0.5D, 0.25D, and 0.125D ($1/2$, $1/4$, and $1/8$ dioptres increments) and provided a two-alternative forced choice judgment on each trial ("one or two"). We took great care to ensure that the refraction method was double masked, in that neither the subject nor the experimenter were aware of the refractive lens choices during the experiment. Lens choices were driven purely by the subject's subjective preferences. We also elected to employ presbyopic subjects as a method for ensuring a stable optical system (zero accommodation) as a means of reducing refractive variability. We also employed a fixed pupil size avoiding natural variability in pupil size and two experienced psychophysical subjects (two of the authors). Thus, we employed all of the control parameters expected to minimise refraction variability. This approach was successful in that repeat refractions rarely varied by more than $1/8$ dioptre, with an average standard deviation of 0.05D for all refractions that employed test stimuli containing high SFs. For the two stimuli lacking high SFs (low SF grating and low-pass filtered Church) refraction standard deviation increased to 0.2D. These results reflect the tight control of optical variation employed in this study, and mirror just noticeable differences in defocus observed in forced choice experiments^{59, 60}. Interestingly, the current refraction data prompt questions about the source of test-retest variability observed in standard clinical refractions⁶¹, where standard deviations of refraction were about 0.3-0.4D. It is likely, therefore, that clinical refractions could be made significantly more accurate if some of the sources of variability generally present during the refraction process can be removed.

It is interesting to note that while Subject One had a radius in focus of almost exactly 1 mm, Subject Two had a radius in focus of approximately 1.5 mm for a 7mm pupil, and subjects in Rocha et al⁵⁸ and Yi et al⁵⁷ indicate radii in focus of 0.8mm and 0.4mm for a 6mm pupil. Since low spatial frequencies refractions are associated with larger radii in focus, the radius

in focus difference between our two subjects may be explained by Subject Two employing lower spatial frequencies than Subject One when performing a subjective refraction. This is possible, but unlikely because both subjects had best spectacle corrected acuities of $>20/15$ and this trend is seen even with stimuli containing a single high SF. An alternative hypothesis states that Subject Two had a larger radius in focus because the SCE is not well centred in this eye, and biased the pupil function to a more peripheral location. Unpublished data collected as part of Rynder's PhD thesis support this hypothesis⁶² because, unlike Subject One who has a well-centred SCE, Subject Two has a decentred SCE with a peak around 0.5mm from the pupil centre.

Acknowledgments

This research was funded by a grant to Arthur Bradley from Essilor International. We greatly appreciate the fabrication of spherical aberration phase plates by Dr. Xin Wei using the laboratory facilities of Prof. Raymond Applegate, University of Houston supported by NEI-NIH R01 EY019105, R01 EY008520, and P30 EY007551.

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Figure 1.

Left side: Four stimuli were used in the first refraction experiment. Top row, three lines of a high contrast visual acuity chart (20/45, 20/40, 20/30 letter size). Middle row a modern cityscape. Bottom row shows low (1.8 cpd, contrast 0.54) and a high (15.5 cpd, contrast 0.2) spatial frequency Gaussian-weighted grating patches. Right side: Test stimuli used in experiment 2. Top, the original image of a church, and middle row is the Gaussian low-pass filtered image of the church, and at the bottom, three types of filtered letter E (letter size

20/50) from left to right: Gaussian low-pass filtered, Gaussian high-pass filtered, and rectangular high-pass filtered.

Figure 2.

Subjective Rx in dioptres relative to paraxial Rx is plotted as a function of spherical aberration levels (μm of C_4^0) with four pupil weighting conditions: uniform (A), normal (B), reverse (C), and double (D). Pupil diameter was 7mm. Error bars are ± 1 SD. Each panel shows subjective Rx data obtained with the four stimuli shown in Figure 1 (VA = Visual Acuity, SF= Spatial Frequency), and the model predictions for paraxial and minRMS refractions.

Figure 3.

Subjective Rx is plotted as a function of pupil weighting, which ranged from -1 to $+2$ times the normal Stiles Crawford Effect (SCE) with high levels of positive (A: $C_4^0 = +0.9 \mu\text{m}$) and negative (B: $C_4^0 = -0.8 \mu\text{m}$) primary spherical aberration. Results are shown for four different test stimuli (VA = Visual Acuity, SF = Spatial Frequency), and the paraxial and min RMS model predictions are included for comparison. Pupil diameter was 7mm. Error bars are ± 1 SD.

Figure 4.

Comparison of model predicted objective refractions²⁶ with experimentally determined subjective refractions for 7mm (A) and 4mm (B) pupils and uniform pupil functions (SCE=0). (A) The spherical Rx that will optimise modulation at each spatial frequency (cycles per degree, cpd) in the presence of $-0.8 \mu\text{m}$ of C_4^0 (dotted curve) and $+0.9 \mu\text{m}$ of C_4^0 (dashed curve). Subjective Rx's (symbols) obtained with 15 and 1.8 cpd gratings are also plotted. Horizontal dotted and dashed lines (Figure 4A) show the subjective refractions obtained with the low-pass filtered Church stimulus (Figure 1) in the presence of negative

and positive SA, respectively. Therefore, the vertical dotted and dashed lines and arrows indicate the spatial frequency (SF) being focussed in these experiments. Objective model predictions and subjective Rx's are plotted in Figure 4B for a 4 mm pupil diameter with C_4^0 rescaled from the 7 mm pupil diameter values shown in Figure 4A.

Figure 5.

Radius within the pupil that is focused by subjective refractions for different pupil weighting conditions (reverse SCE, uniform pupil, normal SCE, double SCE). Data obtained with a 7mm diameter pupil for Subject One (A) and 2 (B). VA = Visual Acuity, SF= Spatial Frequency, SCE=Stiles Crawford Effect.

Figure 6.

Paraxial (dashed line) and minRMS (dotted line) refractions are plotted as a function of pupil diameter. $C_4^0 = -0.8 \mu\text{m}$ (top), and $+0.9 \mu\text{m}$ (bottom) for the 7 mm pupils are scaled by r^4 for all other pupil sizes⁶³. Subjective Rx for 4mm and 7mm pupil diameters obtained with uniform pupil (A) normal SCE (B) for the test stimuli shown in Figure 1. VA = Visual Acuity, SF= Spatial Frequency.

H N D R U
Z V U D N
V P H D E

Figure 7.

Subjective refractions are compared to model predicted paraxial and minRMS refractions as a function of C_4^0 levels. (A) Subject One data obtained with the unfiltered and low-pass filtered church stimuli, (B) and (C) show data for Subject One and Two, respectively, with unfiltered and filtered (Gaussian filters and Rectangular Filters) 6/15 letter E stimuli. With unfiltered letters subjects maximised either a “darker” or “sharper” subjective criterion during refractions.