Published in final edited form as:

Optom Vis Sci. 2010 May ; 87(5): 300–312. doi:10.1097/OPX.0b013e3181d95217.

The Visual Impact of Zernike and Seidel Forms of Monochromatic Aberrations

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Abstract

Purpose—To examine the impact on visual acuity of different aberrations modes (e.g. coma, astigmatism, spherical aberration (SA)) and different aberration basis functions (Zernike or Seidel).

Methods—Computational optics was used to generate retinal images degraded by either the Zernike or Seidel forms of 2nd through 4th order aberrations for an eye with a 5mm pupil diameter. High contrast, photopic visual acuity was measured using method of constant stimuli for letters displayed on a computer-controlled, linearized, quasi-monochromatic ($\lambda=556$ nm) display.

Results—Minimum angle of resolution (MAR) varied linearly with the magnitude (root mean square error, RMS) of all modes of aberration. The impact of individual Zernike lower and higher order aberrations (HOAs) varied significantly with mode, e.g. arc minutes of MAR/micron of RMS slopes varied from 7 (spherical defocus) to 0.5 (quadrafoil). Seidel forms of these aberrations always had a smaller visual impact. Notably, Seidel spherical aberration (SA) had 1/17th the impact of Zernike SA with the same wavefront variance, and about 1/4th the impact of Zernike SA with matching levels of r^4 wavefront error. With lower order components removed, HOAs near the center of the Zernike pyramid do not have a large visual impact.

Conclusions—The majority of the visual impact of high levels of 4th order Zernike aberrations can be attributed to the 2nd order terms within these polynomials. Therefore, the impact of SA can be minimized by balancing it with a defocus term that flattens the central wavefront (paraxial focus) or maximizes the area of the pupil with a flat wavefront. Over this wide range of aberration types and levels, image quality metrics based upon the PSF and OTF can predict VA as reliably as VA measures can predict retests of VA, and thus such metrics may become valuable predictors of both VA and, via optimization, refractions.

Keywords

monochromatic aberrations; visual acuity; Zernike; Seidel; retinal image quality

In the clinical environment, visual acuity (VA) testing is the gold standard, albeit indirect method for assessing optical quality of the retinal image. This surrogate test of retinal image quality forms the basis of subjective refractions for the simple reason that the VA is relatively easy to measure and it varies in direct proportion to the level of defocus, modulated only by pupil size ($MAR = \text{Blur}/4$, where blur = blur circle diameter = defocus

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Potential Conflict of Interest: Thibos and Bradley are named co-inventors on a patent application "System and Method for Optimizing Clinical Optic Prescriptions" # 10/582,470 owned in part by Indiana University.

(D) $\times$ pupil diameter) 1^{-4} . In addition to the well-documented impact of lower order aberrations on VA, more recent studies have shown that higher order aberrations can also degrade VA 5^{-8} . Accordingly, visual acuity continues to be employed clinically as a surrogate measure of image quality when assessing the impact of higher order aberrations (e.g. Best Spectacle Corrected VA in studies of post-refractive surgery, intraocular implants, and keratoconic eyes).⁹⁻¹¹

Increased levels of Higher Order Aberrations (HOAs) introduced by multifocal (aberrated) Intraocular Lenses (IOLs) ¹², multifocal contact lenses ¹³, aberrated custom contact lenses ¹⁴, corneal disease ¹⁵, and refractive surgery ¹⁶⁻¹⁸ can all lead to reduced visual acuity. Conversely, correcting HOAs using deformable mirrors ^{7, 19}, custom lathed optical corrections ²⁰, and aspheric IOLs ¹¹ can improve VA. It appears, however, that not all HOAs have the same ability to degrade vision. Studies using computationally blurred letter charts ⁵, or deformable mirrors ^{8, 21, 22} have shown that individual Zernike modes closer to the center of the Zernike pyramid (lower meridional frequencies) have more impact than those near the edge (higher meridional frequencies).²³

Although individual Zernike polynomials (modes) are considered as individual aberrations, they contain multiple terms. For example, the “spherical aberration” (SA) Zernike polynomial includes both r^4 and r^2 terms and defines the following wavefront error (WFE)

$$WFE = c_4^0 Z_4^0 = c_4^0 \sqrt{5}(6r^4 - 6r^2 + 1), \quad (1)$$

Consequently, the WFE in the central 50% of the pupil is dominated not by the r^4 term (which is approximately zero in the central region of the pupil), but by the opposite sign r^2 term (Figure 1). This structure of individual Zernike modes becomes important because experimental studies have shown that, in eyes with SA, best VA (subjective) refractions for circular pupils are dominated by the central optics ²⁴⁻²⁶. These results suggest that VA is determined primarily by the WFE in the central portion of the pupil, and optimum VA is achieved by flattening the central wavefront. It is clearly possible, therefore, that the observed effect of Zernike SA on VA is due not to the r^4 component of the polynomial (the component that makes it “spherical aberration” and is primarily responsible for the WFE at the pupil margins), but rather by the r^2 term generating spherical defocus-like wavefronts in the pupil center. The Seidel convention for defining monochromatic aberrations, defines SA as $a_4^0 r^4$, and thus lacks the r^2 term that dominates the central region of Zernike SA (Figure 1).

The present study was designed to re-examine the relationship between different types of HOAs and VA, specifically investigating the role of the basis functions for defining aberrations (e.g. Zernike vs. Seidel). We examine the hypothesis that the visual impact of individual Zernike HOAs stems primarily from the lower order components included in each mode. Although it is possible that the complexity of the monochromatic HOAs and their interaction may preclude any simple relationship between VA and aberration level, we also look for pupil plane and image plane metrics that allow accurate prediction of VA in the presence of both Lower Order Aberrations (LOAs) and HOAs.

METHODS

Stimulus Generation

We studied the visual impact of monochromatic HOAs on vision using the approach first described in detail by Burton and Haig ²⁷. This method employs computationally blurred

stimuli, which generate retinal images in the experimental subject's eye degraded only by diffraction and the specific monochromatic HOAs included in the computational model 28· 29. In order to employ this method accurately, the optical degradation of the display monitor and the subject's eye must be pre-compensated within the blur calculations by deconvolving the computed image by the display MTF and the observer's eye OTF. Partial implementation of the Burton and Haig method has been used previously to examine the impact of HOAs on VA.5· 30

All optical computations employed a 5 mm pupil. The display non-linearity and its two-dimensional MTF as well as the subject's OTF were measured and pre-compensated in the image calculations. Monochromatic aberrometry measurements (Wavefront Sciences, COAS) across the central 2.5 mm pupil confirmed that the subjects' OTFs were within a couple of percent of diffraction limit, and thus during the experiment subjects used a 2.5 mm artificial pupil and their optics were represented in the pre-compensation process by the diffraction limited OTF of a 2.5 mm pupil. The display MTF was determined empirically by displaying a series of high contrast, sinusoidal gratings and then measuring the displayed contrast and phase using SpectraScan PR714 (Photo Research) radiometer configured with a 2-pixel wide, rectangular measurement window oriented parallel to the gratings. These measurements were corrected for the OTF of the measurement window and extrapolated to the cutoff frequency of the display. Separate MTFs for horizontal and vertical gratings were radially interpolated to produce a 2D MTF used to pre-compensate the stimulus.

Accuracy of image computation was verified using a number of benchmarks. Corrections for display nonlinearity (gamma correction) and low-pass filtering were confirmed experimentally. The images generated from wavefronts defined in terms of Zernike basis vectors (our methods) were identical to those generated using van Meeteren's methods 31. MTFs and PSFs for diffraction-limited cases were closely predicted by diffraction theory. Spherical defocus (1 diopter) generated image contrast minima and phase reversals at the same spatial frequencies as expected from geometrical optics theory. Also, by imaging the computer display through a simple model eye, computationally blurred images were compared directly to optically blurred images. Images were captured by a CCD (the model retina) with the optical system well focused and the displayed images blurred, or with well focused displayed images and a defocused optical system. As shown in Figure 2, the results from the two methods were essentially identical for both spherical and astigmatic blur thus confirming the accuracy of our computational blurring methods.

Psychophysical Experiment

High luminance (264 cd/m^2) quasi-monochromatic (17 nm full width at half height) test stimuli were generated with a digital projector and rear projection screen viewed through an interference filter (peak transmission, 556 nm). Three adult subjects participated in this study, each experiment was performed on two subjects and all data reported are the means of the two individuals. All subjects had corrected visual acuity better than 20/20. They were carefully refracted in the instrument and viewed the display through a unit magnification telescope, which imaged the 2.5 mm artificial pupil into the geometric center of the subject's natural pupil, which was stabilized using a bite-bar (Figure 3). To ensure that computed image and neural image were matched in size, a unit magnification telescope was set up with a 2.5 mm artificial aperture that was located 2.5m from the 512 by 512 pixel display, which subtended 3.26 degrees. This geometry ensured that the spatial frequencies within the OTF were the same as those in the stimulus amplitude spectrum. The artificial pupil of the system was conjugated and centered with the entrance pupil of the subject's eye.

The computational compensation for the display MTF and eye OTF essentially acts as high-pass filtering of the computed image (Figure 4). Such filtering prevented us from employing

high contrast stimuli and high spatial frequencies (need to divide by very small numbers near to display or eye cut-off), and thus all visual acuity (VA) measurements were band-limited to 38 cpd (20/16 VA) and generated with 30% to 21% contrasts to ensure that the pre-compensated images remained within the 8 bit dynamic range of the system. Intensity profiles and amplitude spectra of a 30% contrast 20/40 letter (thin solid line) imaged with 0.05 microns of Spherical aberration (SA) (Figure 4a and b) emphasize the increase in the intensity range of the displayed letter when it has been pre-compensated by the deconvolution process described above (dashed lines). This figure also shows the difference between the desired retinal image (thick solid line) and the one that would be achieved if the deconvolution process had not been implemented (dotted line).

For comparison, retinal images were also computed for the same stimuli if no pre-compensation was performed and the stimuli were viewed polychromatically. In the latter case, the retinal image is blurred by the display, and the eye's optics and differs substantially from the desired image. Control experiments show that, if the pre-compensation is not implemented, VA can be degraded by slightly more than 0.1 log units by the additional degradation of display and subject's OTF. The impact of the additional filtering varies with the level of filtering generated by the computational optics.

We used a forced-choice method of constant stimuli (4-AFC and 10-AFC for the tumbling E and Sloan letter acuity, respectively) to generate psychometric functions of percent correct identification vs. letter size. A random sequence of 8 to 12 letter sizes (0.05 logMAR steps) with 10 or 20 presentations per letter size constituted a single experimental run that generated a single psychometric function. A fixation box (30% contrast twice the size of the largest letter presented within a given trial) was presented throughout the trial to aid fixation. All letters were dark on a light background with a stroke width of 1/5th the letter height and a 1:1 aspect ratio.

Individual aberrated letters were presented for 0.5 seconds (signaled by a tone) and the subject's task was to indicate which letter was present by pressing a key. To avoid learning effects, no feedback was given about correctness of responses. Visual acuity was determined by fitting the psychometric functions with a Weibull function of the form

$$P(w)=1 - (1 - \gamma)\exp\left[-\left(\frac{w}{\alpha}\right)^\beta\right], \quad (2)$$

where P is the probability of a correct answer, γ is the rate of guessing (0.25 for 4AFC, 0.1 for 10AFC), α is the inflection point, β is proportional to the steepness of the function when plotted on semi-log coordinates and w is the stroke width of the letter. Minimum angle of resolution (MAR) is the interpolated stroke width corresponding to criterion performance of $P_c=62.5\%$ and $P_c=55\%$ correct identification for the tumbling E and Sloan letters, respectively. Solving equation 2 for w gives MAR explicitly as

$$MAR=\alpha\left[-\ln\left(\frac{1-P_c}{1-\gamma}\right)\right]^{\left(\frac{1}{\beta}\right)}, \quad (3)$$

The 10 letters (C,D,H,K,N,O,R,S,V,Z), originally used by Sloan 32 exhibit similar resolution (range approximately 0.15 logMAR) when intermixed in a resolution task when focused 33' 34 but are slightly more variable when defocused 34. Subjects provided informed consent, and the experimental protocols were approved by Indiana University IRB.

Aberration Parameters

Monochromatic aberrations are often described using Seidel or Zernike formats [35], and these two types of aberration basis function differ in a systematic way. For example, Zernike astigmatism describes the wavefront that will create a “circle of least confusion” image (half way between either line foci) that is myopic along one primary meridian and hyperopic along the orthogonal meridian (Figure 5). Seidel astigmatism, however, defines the wavefront that will generate one of the line foci and concentrate the defocus at the orthogonal meridian. Likewise, Zernike SA describes a wavefront that modulates its defocus sign as a function of radial distance, e.g. from a hyperopic center to a myopic surround for positive Z_4^0 . Seidel SA, on the other hand describes a wavefront that is well focused centrally and either myopic or hyperopic at the pupil margins. Not surprisingly, Seidel and Zernike aberrations generate quite different PSFs (Figure 5). Similarly, Zernike secondary astigmatism distributes the WFE across meridian and radial position, whereas our “Seidel” form of secondary astigmatism retains one meridian and the pupil center well focused and thus concentrates the WFE toward the pupil margins and along meridians orthogonal to that which is focused.

The wavefront aberration function (WAF) for Seidel spherical aberration is

$$W(r, \theta) = a_4^0 S_4^0 = a_4^0 r^4, \quad (4)$$

where a_4^0 is the Seidel coefficient of the polynomial $S_4^0 = r^4$. When balanced by defocus to minimize RMS wavefront error, the result is Zernike spherical aberration

$$WFE = c_4^0 Z_4^0 = c_4^0 \sqrt{5}(6r^4 - 6r^2 + 1), \quad \text{where } c_4^0 = \frac{a_4^0}{6\sqrt{5}} \quad (5a)$$

Thus we can express Zernike spherical aberration using Seidel aberration coefficients as

$$W(r, \theta) = a_4^0 r^4 - a_4^0 r^2 + a_4^0 / 6, \quad (5b)$$

The key feature of the two WAFs defined by equations (4) and (5b) is that they have identical amounts of r^4 aberration. Thus, if the visual effects of spherical aberration are dominated by the r^4 term, then these two WAFs should have identical visual effects. Since the r^4 term is the only term that qualifies these WAFs as higher-order aberrations, the above prediction is the natural choice for a null hypothesis. A counter-hypothesis arises, however, if the visual effects of these WAFs are dominated by the r^2 term. If this is true, then the WAF in (4) should have less visual impact compared to (5b) because the r^2 component of Zernike spherical aberration causes paraxial defocus. A third hypothesis is that image quality in eyes is determined by the amount of RMS wavefront error. If this is true, then the WAF in (4) should have a greater visual impact than that in (5b) because it has fourfold larger RMS because of the Z_2^0 required to cancel the r^2 term within Z_4^0 .

$$RMS(a_4^0 S_4^0) = \sqrt{[(c_2^0)^2 + (c_4^0)^2]} \quad \text{where } c_2^0 = \sqrt{15} \times c_4^0 \quad (5c)$$

In short, by comparing the visual impact of WAFs (4) and (5b) we can test three alternative hypotheses that predict the effect of Seidel spherical aberration is smaller than, equal to, or greater than the effect of Zernike spherical aberration. A similar line of reasoning can be applied also to other modes of higher-order aberrations (e.g. 4th-order astigmatism), but not coma, for which monochromatic images generated with Zernike and Seidel coma differ only in prism (position).

A Zernike expansion of the wavefront aberration W as a function of the polar pupil coordinates (r, θ) is

$$W(r, \theta) = \sum_{n,m} c_n^m Z_n^m(r, \theta), \quad (6)$$

where c_n^m are scalar coefficients applied to the Zernike circle polynomials Z_n^m of radial order n and meridional frequency m .³⁶ A Seidel expansion is a power series³⁵ written in analogous form as

$$W(r, \theta) = \sum_{n,m} a_n^m S_n^m(r, \theta), \quad (7)$$

where a_n^m are scalar coefficients applied to the Seidel polynomials S_n^m of radial order n and meridional frequency m . According to (6) a given Seidel aberration can be expanded into a weighted sum of Zernike aberrations, and according to (7) a given Zernike aberration can be expanded into a weighted sum of Seidel aberrations. Thus an individual aberration in one system is a combination of aberrations in the other system.³⁷

The relationship between Seidel and Zernike aberration coefficients was established by performing a Zernike expansion of individual Seidel modes³⁵. For example, the wavefront aberration function for Seidel astigmatism is

$$W(r, \theta) = a_2^2 r^2 \cos^2 \theta = a_2^2 r^2 (1 + \cos 2\theta) / 2, \quad (8)$$

which has the Zernike expansion

$$W(r, \theta) = c_2^0 \sqrt{3} (2r^2 - 1) + c_2^2 \sqrt{6} (r^2 \cos 2\theta) + c_0^0, \quad (9)$$

Since these two expansions describe the same wavefront, the coefficients for the $r^2 \cos 2\theta$ term in equations (8) and (9) must be equal. Likewise, the coefficients for the r^2 terms must be equal. This equivalence leads to the desired relationship between the Seidel and Zernike coefficients,

$$a_2^2 = c_2^0 4 \sqrt{3} = c_2^2 2 \sqrt{6}, \quad (10)$$

By this method we determined the combination of Zernike coefficients needed to generate all of the desired Seidel aberrations.

The overall blurring strength of a wavefront aberration function was quantified by root mean squared (RMS) wavefront error, computed as the square root of the sum of squared Zernike coefficients. Microns of RMS wavefront error were converted to diopters of equivalent defocus M_e 26 with the linear equation

$$M_e = 4\pi \sqrt{3} \frac{RMS_{error}}{area_{pupil}}, \quad (11)$$

Spherical blur levels in our experiments ranged from 0.23 to 3.61 μm of RMS error, which corresponds to 0.25 to 4.00 D of equivalent defocus. Examples of visual stimuli blurred by 0.5 D of Zernike and Seidel aberrations are shown in Fig. 5. The differences in the images created from these RMS matched Zernike and Seidel aberrations are striking.

RESULTS

Complexities in the Psychometric Functions

A typical psychometric function (Figure 6a) exhibits a monotonic, but non-linear relationship between stimulus strength and visual performance. When fit with a suitable function (Weibull, in our case) they are generally described by two parameters: The horizontal position of the function (alpha) determines threshold, while the slope (beta) provides evidence of the experimental noise (internal to the observer and/or external). The Weibull function provides an excellent fit for these data, with r^2 values in excess of 0.9. Consistent with previous studies of VA psychometric functions 33, 38–40, we find that most psychometric functions extend over about 0.2 and 0.4 logMAR.

Due to the oscillating nature of the defocused MTF and its corresponding oscillating impact on the human contrast sensitivity function 41, it is possible to obtain non-monotonic psychometric functions that oscillate over a range of letter sizes (and thus spatial frequencies). Although these were rarely observed when using the Sloan 10 letter set, they were commonly encountered when measuring tumbling E VAs (Figure 6), presumably because the E is the most grating-like of all letters. In the non-monotonic psychometric functions (Figure 6b and c), the performance drops as image contrast dips (see inserts) and further decreases in letter size produce increased performance when the image contrast increases irrespective of whether the characteristic frequency (e.g. 2.5 c/letter) has correct phase (Fig. 6c) or is phase reversed (Fig. 6b).

Interpretation of the non-monotonic psychometric functions is complex. We have the option of defining MAR as the smallest letter size for which performance achieves the criterion (e.g. 55% correct), or the largest letter size that drops to this criterion. We adopted the rule of recording VA as the largest letter size for which performance drops to our criterion threshold level (half way between chance perfect performance, or 55% for Sloan VA and 62.5% for tumbling E VA).

Relationship between Magnitude of HOAs and Visual Acuity

A careful review of previous literature 4 revealed a simple linear relationship between spherical blur magnitude and the minimum resolvable spatial detail (minimum angle of resolution, MAR) in which $MAR = \text{Blur Circle diameter}/4$. This simple relationship can be generalized to the sphero-cylindrical blur 3. We have examined this relationship for a series of individual Zernike aberrations (Figure 7), and find that for each Zernike mode, a linear relationship exists between the magnitude of the aberration (RMS) and MAR. R^2 values from linear regression are, with one exception, all above 0.9, with a mean value of 0.95.

Linear regression of the RMS values against logMAR produced significantly lower R^2 ($p < 0.01$) emphasizing that the linear relationship between blur and MAR for lower order aberrations also holds true for the higher order aberrations.

The results for Tumbling E and Sloan visual acuity are very similar. Although the overall impact of aberrations was generally higher for tumbling E than for Sloan, the relative impact of each mode was almost the same. As shown previously, there are striking differences between the impact of individual aberrations. We have quantified the visual impact of individual Zernike modes by the slope of the functions shown in Figure 7 in arc minutes of MAR per micron of RMS, which range from 7.52 (SA and tumbling E) to 0.5 (quadrafoil, tumbling E and Sloan). The Sloan VA slope data are plotted as a function of radial order and meridional frequency in Figure 8 (top panel). The shows the impact of individual Zernike modes arranged in a Zernike pyramid. Although the highest meridional frequencies clearly have the smallest impact, there is no consistent relationship between slope and frequency (f) in that slopes for $f=0$ and $f=2$ are both higher than those for $f=1$ (coma). The top panel also shows that there is no systematic relationship between the radial order of individual Zernike modes and their impact on VA.

Smith 42 has shown that $MAR = B/4$ for spherical defocus, and $B = \text{blur circle diameter in radians} = P \cdot D$. Thus, for our experiment in which a 5 mm pupil is used, the prediction is that $MAR = 5 \cdot 10^{-3} / 4 \text{ radians/D}$ or 4.3 arc minutes per diopter of defocus. Converting our Sloan VA data obtained with spherical blur from minutes/micron RMS to minutes/Diopter using equation 11, we observe that spherical defocus degrades VA by 4.6 min/D. For a given RMS value, the wavefront vergence along the primary meridians of the astigmatism will be square root of 2 less than that observed with spherical defocus with the same RMS 43, and thus the associated blur size at the circle of least confusion will be square root of two smaller. As predicted, therefore, our data show that the impact on Sloan VA of second order Zernike astigmatism is root 2 lower than that observed with spherical defocus (see Figure 7 top right panel) when evaluated in terms of RMS confirming that the impact of both second order Zernike defocus and astigmatism both exhibit the same relationship in which $MAR = B/4$. Using the conversion from RMS to equivalent diopters (the diopters of spherical defocus that would generate a given RMS, equation 11) we found this approximate relationship to be generalized to Zernike SA, which had slopes of 4.6 arcminutes/ D_{eq} .

Impact of Aberration Basis Functions on their Visual Effect

We have examined the visual impact of Zernike and Seidel versions of primary astigmatism and three aberrations of the fourth order (Spherical aberration, and both forms (H/V and oblique) of secondary astigmatism). Sloan VAs were similarly affected by primary oblique astigmatism with a circle of least confusion image (Zernike) or a line focus (Seidel). This was not true, however for H/V astigmatism. Tumbling E VA was much more resistant to Seidel H/V astigmatism than to Zernike H/V astigmatism. Slopes (minutes of arc MAR per micron of RMS) were 16 times higher for Zernike H/V astigmatism. There was a small difference for Sloan VA too (slopes 1.6 times higher for Zernike H/V astigmatism than Seidel).

The most striking differences between Zernike and Seidel forms of individual aberrations were observed with 4th order aberrations for both tumbling E and Sloan VA (Figure 9). The impact of Zernike 4th order aberrations is much greater than that of 4th order Seidel. The Zernike slopes (arcminutes of MAR/microns of RMS) are 35, 17 and 29 times greater than those generated by 4th order Seidel aberrations of oblique secondary astigmatism, spherical aberration and H/V secondary astigmatism, respectively (Figure 9, left column). These data emphasize the importance of basis function when defining individual aberrations, and challenge the notion that SA is a visually significant aberration. For example, the visual

impact of Seidel SA (slope of the data shown in Figure 9) is only 60% that of the slope of Zernike quadrafoil (Figure 7), the latter of which is generally considered to be of minor visual importance.

The data plotted in Figure 9 allow us to test the initial hypotheses outlined in the methods. As pointed out in the methods, Seidel SA will have 4 times the RMS of the Zernike SA with matching levels of r^4 because the coefficient of Z_2^0 required to cancel the r^2 term in Z_4^0 must be square root of 15 larger than the C_4^0 . Therefore, because the slopes of MAR vs RMS differ by a factor of 17 for Zernike SA and Seidel SA, the MAR vs r^4 slopes will differ by 17/4 (Figure 9, right column). That is, for matched levels of r^4 , high levels of Zernike SA has 4.25 times the impact of Seidel SA, confirming that the visual impact of SA cannot be attributed solely to the level of r^4 terms (reject hypothesis 1 for SA). A similar rule applies to secondary astigmatism. Our version of Seidel secondary astigmatism uses Z_2^2 to cancel the $r^2\cos 2\theta$ terms in Z_4^2 to generate paraxial focus, and also adds Z_4^0 and Z_2^0 to generate a line focus. Because of these additional terms, the RMS of Seidel secondary astigmatism is 5.5 times greater than Zernike secondary astigmatism with matching levels of $r^4\cos 2\theta$ terms. Thus, in terms of $r^4\cos 2\theta$, a high level of Zernike secondary astigmatism is between 35/5.5 and 29/5.5 (about 5 or 6) times more visually detrimental than Seidel secondary astigmatism (Figure 9 right column). It is clear, therefore, that although Zernike and Seidel SA and secondary astigmatism share common 4th order terms (r^4 for SA and $r^4\cos 2\theta$ for secondary astigmatism), most of the visual impact of the Zernike forms of these aberrations cannot be attributed to these 4th order terms.

The above analysis suggests that the primary factor determining the visual impact of Zernike 4th order aberrations must be the second order terms included within the polynomials (e.g. see equation 1). This hypothesis, outlined in the methods section, also predicts that Zernike 4th order aberrations will have a much larger visual impact than the Seidel forms, as shown to be true in Figure 9. Although the above analysis supports the hypothesis that it is the second order components of the 4th order Zernike aberrations that are responsible for their large visual impact, it does not distinguish between two alternative explanations. First, the r^2 terms within the 4th order Zernike polynomials may be entirely responsible for their visual impact, and essentially act independent of the coexisting r^4 terms. Second, although the r^2 terms are primarily responsible for the visual impact of the 4th order Zernike aberrations, their effect is not independent of the r^4 terms. We have discriminated between these two possibilities by comparing the impact on MAR of the r^2 WFE when alone (Z_2^0), and in the presence of r^4 (Z_4^0). For a given level of RMS, there is square root of 15 greater r^2 in Z_4^0 than in Z_2^0 . Therefore, although the Zernike Z_2^0 and Z_4^0 data in Figure 7 indicate similar impact of defocus and Zernike SA on MAR (slopes of 6.1 and 5.7 minutes per micron of RMS, respectively), there is approximately 4 times more r^2 in the Z_4^0 than the Z_2^0 . This means that the r^2 within the Z_4^0 wavefront is only about 23% as visually detrimental as the r^2 within Z_2^0 . Therefore, although the majority of the visual impact of Z_4^0 comes from its second order component, this r^2 term has considerably less impact when in combination with the opposite sign r^4 term.

We have plotted the visual impact of individual Seidel aberrations (arcminutes of MAR/ microns of RMS) as a function of the meridional frequency and radial order in the bottom pyramid of Figure 8. Note that the Seidel SA, although at the pyramid center, generates one of the smallest visual impacts. The Seidel aberration data do show that lower order aberrations have a much larger impact than do higher order aberrations, irrespective of their meridional frequencies. This result is consistent with the idea that the large visual impact of low meridional frequency Zernike modes is due to the lower components of these Zernike modes.

DISCUSSION

One of the driving forces behind the investigation of HOA in human eyes is the recent technological advances that enable contact lenses 44, inter-ocular lenses 45 and photoablative refractive surgeries 46 to include corrections for higher order monochromatic aberrations. However, significant technical challenges for successful correction of ocular HOAs remain. For example, many of the HOAs are very small (e.g. 26) and would require sub-micron accuracy in the correction method. Also, HOA corrections can only be successful if the correction is prevented from decentering and rotating 47–49. These two challenges to successful correction of HOAs emphasize the need to identify those aberrations that are visually most significant and least susceptible to rotation and decentration.

Our data (figure 7) show that the visual impact of all the individual aberration modes increases linearly with aberration magnitude (RMS), emphasizing that the visual impact of all HOAs, like that of lower order aberrations 3rd 4, is directly proportional to their amplitude, which in turn emphasizes the value of correcting the higher magnitude HOAs. The fact that ocular aberration levels drop logarithmically with increasing radial order and meridional frequency 26 suggests therefore that HOA corrections should concentrate on the larger 3rd and 4th order aberrations of coma, trefoil, and SA. The complicating factor is that not all aberration modes have equal visual impact (Figures 7 and 9). Even more challenging is the realization that even for a single aberration type (e.g. SA), its visual impact depends critically upon the optical basis functions used to define the aberration (e.g. Seidel vs. Zernike). For example, one of the most important findings of this study is that the visual impact of SA, considered to be perhaps the most visually important HOA 5th 22, depends critically upon the basis function used to define it.

The data in figure 9 emphasize that the visually impact of Zernike SA is due mostly to the lower order r^2 term within the Zernike SA, and as such is not primarily a HOA effect. The Seidel SA impact (slope (minutes of arc/micron of RMS) = 0.3 (E's) and 0.38 (Sloan)) is only 4% to 10% that of the Zernike SA (slopes = 7.52 (E's) and 3.9 (Sloan)). Therefore, although there are two advantages of selecting SA for correction (the population mean is not zero 26 and it will be tolerant to lens rotation errors), our Seidel results suggest that, if optimally balanced by defocus, SA may have only minor visual importance.

The SA results imply, therefore, that in the presence of high levels of SA, spherical power adjusted to ensure paraxial focus will generate improved VA compared to the same eyes with spherical power adjusted to achieve minimum RMS. That implication is consistent with results from a population of adults 26 indicating that a typical dilated subjective refraction (sphere power that maximizes VA) provides an approximate paraxial correction 50. That is, in the presence of significant SA, subjective quality for small high contrast letters is optimized by a sphere correction that approximately focuses the light passing through the pupil center. Such a prescription would, therefore, dramatically reduce the impact of ocular SA.

Previous work 30–51 using stimulus blur methods similar to those used in the present study also found that the visual impact of SA mostly disappeared when defocus was adjusted to approximate paraxial focus. However, earlier results from our lab 52 with lower and more typically experienced levels of SA (0.09 to 0.45 microns of RMS) showed that optimal focus transitioned from minimum rms ($Z_2^0 = \text{zero}$) with the lowest level of SA to a defocus level about half way between minimum rms and paraxial focus with higher levels of SA. That is, in every case studied, except for the 0.09 microns of SA tested by Cheng et al, adding some

Z_2^0 spherical defocus of the same sign as the Z_4^0 produced significant reductions in the visual impact of the SA.

The impact of adjusting the second order spherical defocus term (Z_2^0) on the resultant wavefront produced by spherical aberration (Z_4^0) can be seen in Figure 10 where we show the WFE across a 5 mm diameter pupil for three different levels of Z_4^0 (0.09, 0.21, and 0.54 microns) when Z_2^0 is set to zero (panel A), when Z_2^0 is adjusted to obtain paraxial defocus (r^2 terms set to zero, panel B), and when Z_2^0 is adjusted to maximize the area of the pupil with a flat wavefront ($WFE < \pm \lambda/4$, panel C). When SA is small ($Z_4^0 = 0.09$ microns), setting Z_2^0 to zero (the refraction that will minimize RMS) will achieve the largest pupil area with a flat wavefront. However, as SA levels rise, paraxial focus produces a larger central flat region of the wavefront, and the central flat region can be further increased by selecting a defocus term that is between the minimum RMS and paraxial refractions. This trend is quantified in Figure 11A, which shows that the required Z_2^0 term required to maximize the proportion of the pupil with a flat wavefront increases as level of SA increases, but is always slightly less than that required to achieve paraxial focus.

The impact on image quality of the three different strategies for refracting an eye with SA described in Figures 10 and 11A was evaluated by plotting the MTF (Figure 11B) for each condition in the presence of a high level of SA (0.54 microns). These MTFs show that with a minimum RMS refraction (set Z_2^0 to zero) Z_4^0 produces a defocus-like MTF which drops to zero at about 8 c/deg and oscillates with accompanying phase reversals beyond this MTF zero 53. This MTF shares much in common with that produced by spherical defocus with the same rms (thin lines in Figure 11B). Unlike the defocus MTF, however, the Z_4^0 MTF does not introduce the same phase reversals. In contrast, when the r^2 term is zeroed (paraxial focus), the MTF oscillations are eliminated, emphasizing that they are produced by the r^2 term imbedded in the Zernike SA polynomial. The defocus level between minimum RMS and paraxial focus that maximizes the flat region of the wavefront (Figure 10c) also avoids the MTF oscillations and produces higher levels of image modulation than either the paraxial or minimum RMS refraction. Thus for eyes with high levels of SA (e.g. post refractive surgery eyes 17, 54, 55), a refraction strategy that flattens the central wavefront should be considered. Figure 12 shows an example image of a letter chart generated with a 6 mm pupil and 0.4 microns of Z_4^0 with a minimum rms refraction as specified by equation 5 (image outside of circle) compared directly with that generated with the same amount of r^4 as specified by equation 4 with paraxial focus (inside of circle). This image clearly shows that Seidel SA produces a high bandwidth but low contrast image (inside circle), but Zernike SA removes the high frequencies.

The above analysis and the experimental data reported in this study emphasize that the impact of SA on VA can be minimized by careful selection of the accompanying defocus term. Indeed, a spherical refraction that maximizes the fraction of the pupil area for which the wavefront is reasonably flat will produce a full bandwidth image with high spatial frequency image contrast similar to those produced by 0.1 diopters of defocus. Thus, with an appropriate choice of spherical refraction, even large amounts of ocular SA will have little impact on high contrast VA because of the long tail of the MTF. However, SA will lower image contrast over a wide range of spatial frequencies (Figure 11b), and thus will lower contrast sensitivity over the same SF range. It is likely, therefore, that correcting SA will have a minor effect on high contrast VA, but a more significant effect on contrast sensitivity or low contrast VA, as has been found in recent studies.^{6, 56-59}

In the present study, Zernike 3rd order coma, trefoil, secondary astigmatism and quadrafoil all have a larger visual impact than Seidel SA. Since quadrafoil and secondary astigmatism tend to be very small in normal eyes 26, our results suggest that, as long as defocus terms

can be optimized, then coma and trefoil may be the visually most important aberrations to correct, or to avoid introducing via refractive surgery.^{54, 60, 61}

The above analysis shows that no single wavefront characteristic (r^4 , r^2 or RMS) can account for the visual impact of different modes of higher and lower order aberrations or different types of the same aberration (Zernike or Seidel). These findings confirm earlier attempts that failed to predict VA as a function of HOA RMS and other characteristics of the wavefront^{5, 21, 52, 62}. However, for both defocus and astigmatism, the single image plane metric of blur size (blur vector length)³ is highly correlated with the resulting VA. Also, several studies of HOAs^{21, 52, 62, 63} have reported that there are characteristics of the image blur (PSF and OTF) that, irrespective of the aberration type, correlate highly with experimental measures of VA or perceived visual quality. Indeed, when combining image-plane measures of optical quality with a formal letter recognition model Watson and Ahumada⁶⁴ were able to predict the actual VA observed in the presence of a range of aberration levels and types with a high degree of accuracy.

The wide range of types, magnitudes and combinations of aberration employed in this study offer an opportunity to identify image plane metrics that correlate with VA that will be generalizable to most optical situations. The current study employed both Zernike and Seidel forms of aberrations originating from varying amounts of nine different modes (defocus, primary astigmatism, coma, trefoil, SA, secondary astigmatism, and quadrafoil) from three subjects, with a total of 296 VA measurements. We employed a series of 31 metrics described by Thibos et al⁵⁰, most of which are image plane metrics and some include neural filtering properties of the eye. Two scatter plots showing image plane optical quality metrics that offer a high predictive value for VA are shown in Figure 13. These data include the variance contributed by two different VA tasks (tumbling E, and Sloan) three observers, and the inherent variability in VA measurements. Principal component analysis produced correlation coefficients of 0.87 and 0.86 indicating that VA can be reliably predicted by these two image plane metrics. Interestingly, both metrics employ neural weighting of the optical PSF (neural Sharpness, NS, ⁵⁰) and the optical MTF (visual Strehl ratio derived from the MTF, VSMTF), and thus as anticipated, these data emphasize that VA is best predicted by considering both optical and neural factors. Thus, the more general linear equation (more general than Smith's lower order aberration equation: $MAR = B/4$) relating image quality to MAR can be restated in terms of the neurally weighted PSF height ($\log MAR = 0.54 \times -\log NS - 0.1572$) or the neurally weighted MTF ($\log MAR = -0.5829 \times \log VSMTF - 0.24$). These results are similar to those observed on a previous data set.⁵²

An image quality metric that is highly correlated with VA can prove extremely valuable in that it can be employed as a predictor of VA, and thus can act as a surrogate for actual VA testing. In order to assess the value of these metrics for predicting VA we quantified the mean residual error (RMSE) expected from the linear models defined above. In both of the above cases, RMSE is 0.10 logMAR. That is the mean VA error anticipated by using these linear models will be 0.1 logMAR. Interestingly, when the retinal image is degraded by defocus, test-retest differences in VA are on average about 0.1 logMAR⁶⁵. Therefore, although the above image quality metrics are not perfect at predicting VA, they are about as good at predicting VA in the presence of image blur as a standard clinical VA measure, and as such may qualify as an effective substitute for actual VA measurements and thus may be employed as an objective substitute for subjective refractions⁵². Using the Cheng et al⁵² aberration and VA data, Watson and Ahumada⁶⁴ were able to employ a template-matching model that included estimates of neural noise and customized model parameters to predict actual Sloan VA with RMSE as low as 0.056 logMAR. It is important to emphasize, however, that the image quality metrics and the VA measures used in this analysis are both monochromatic, and it has yet to be determined whether monochromatic measures of image

quality can predict VA under the more typically encountered polychromatic lighting conditions.

Acknowledgments

Funded in part by NIH grant NEI R01 EY 05109 awarded to Larry Thibos. Psychophysics software written by Kevin Haggerty.

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Figure 1.

The two components (r4 and r2, dotted and dashed lines, respectively) that comprise Zernike SA (solid line).

Figure 2. Examples of images produced by optical blur (optical method, top row) and blur simulation (computational method, middle row) at different defocus and astigmatism levels. Bottom row shows the vertical cross-sectional profiles of images blurred optically (solid lines) and computationally (dotted lines).

Figure 3. Apparatus for the psychophysics experiments (details in the text) BS1 and BS2 are beam splitters used during alignment. f is the focal length of the lenses.

Figure 4.

Top panel shows central vertical slice through the intensity map across of a 20/40 letter E. The thin solid, bold solid, dotted, and dashed lines represent intensity profiles across the stimulus, the desired retinal image, the anticipated retinal image if no-precompensation (deconvolution) was employed, and the computed image after precompensation has been implemented, respectively. The lower panel shows the horizontal amplitude spectra for the same letter and the same 4 conditions. A model with 0.05 microns of SA was used.

Figure 5.

Point-spread functions, wave aberration maps (0.2μm contour interval) and simulated blurred letters (from left to right) of individual Zernike and Seidel primary astigmatism ($Z_{2\pm 2}$ and $S_{2\pm 2}$), spherical aberration (Z_{40} and S_{40}) and secondary astigmatism ($Z_{4\pm 2}$ and $S_{4\pm 2}$). The amount of blur in every case is 0.50D equivalent defocus (5mm pupil and 556nm wavelength). Letter height is 45 arc minutes (20/180 clinical equivalent).

Figure 6.

Examples of psychometric functions from acuity experiments using the Sloan (A) and tumbling E (B and C) letter sets blurred by 0.9 microns of Z40 (A, B) and 0.9 microns of Z22 (C). Symbols show percentage of correct at each letter size. Solid lines are Weibull functions fit to the data by the method of least-squares. Inset images show selected examples of the visual stimulus.

Figure 7.

Average tumbling E and Sloan visual acuities (MAR) from two subjects are plotted as a function of RMS for single Zernike modes. Top panels: Z20 (filled circles), Z22 (solid triangles), Z2-2 (open triangles). Middle panels: Z31 (squares), Z33 (triangles). Bottom panels: Z40 (circles), Z42 (solid triangles), Z4-2 (open triangles), Z44 (solid diamonds), Z4-4 (open diamonds). All coefficients were positive.

Figure 8.

Visual impact (slope of the Sloan MAR (arc minutes) vs. aberration magnitude in RMS (microns) for the 2nd - 5th order Zernike aberration modes tested (see Figure 7) is plotted in the top pyramid. Radial order and meridional frequency are indicated on the Y and X axis, respectively. The visual impact of each aberration mode is indicated by the gray level, and the actual slope values are given for each mode. The same analysis was performed on the Sloan VA data obtained with Seidel forms of these aberrations (from Figure 9) and plotted in the bottom pyramid. X's indicate modes that were not studied.

Figure 9.

This Figure compares Zernike (circles) and Seidel (triangles) versions of the fourth order aberrations Secondary Astigmatism (Z_{4-2} vs. S_{4-2} and Z_{4+2} vs. S_{4+2}) and Spherical Aberration (Z_{40} and S_{40}) as a function of wavefront RMS (left column) and as a function of the magnitude of the r^4 term (Seidel r^4 coefficient, right column). Open symbols show Sloan VA data and filled symbols show tumbling E VA data. All coefficients were positive.

Figure 10.

WFE in microns is plotted across a 5 mm diameter pupil for three different levels of SA. $Z_{40} = 0.09$ (solid line), 0.21 (dotted line), and 0.54 (dashed line). WFE with Z_{20} set to zero (minimum rms refraction) is shown in panel A, with r_2 set to zero (paraxial refraction) in panel B and with a level of Z_{20} that maximizes the region of the pupil with a WFE $< \pm 1/4$ in panel C. Shaded bar represents a range of WFE $< \pm 1/4$ ($l = 0.6$ microns). Horizontal arrows show the pupil diameters for each case that include WFE $< \pm 1/4$. In each case, piston term has been adjusted to achieve zero WFE at the pupil center.

Figure 11.

A: A plot showing the level of defocus (diopters) required to achieve different types of refraction in the presence of differing levels of SA (Z40 microns) for a 5 m pupil diameter. Solid and dashed lines represent the cases of minimum rms and paraxial focus refractions, respectively. The circles and short dash line show the cases of refractions that maximize the metrics PFSt and VSOTF 50, respectively. B: MTFs computed for 600 nm, 5 mm pupil diameter with 0.54 microns of Z40 and plotted on log modulation, and log spatial frequency axes. The minimum rms, paraxial and optimal refractions (solid line, dashed line, and circles, respectively) are compared to the case of 0.1D of spherical defocus (triangles), spherical defocus with 0.54 microns of rms (0.6 diopters, thin line) and a diffraction limited MTF (upper solid line).

Figure 12.

Simulated monochromatic image (6 mm pupil diameter) of a high contrast letter chart imaged with 0.4 microns of Zernike SA (Z40, outside of the circle), and with Seidel SA containing the same level of r_4 (inside of the circle). The 20/20 line (logMAR 0.0) contains the letters DHEVP.

Figure 13. Scattergrams showing the relationship between two image plane metrics of optical quality (log Neural Sharpness (A), and log Visual Strehl Ratio obtained from the MTF (B)) and logMAR VA. Lines represent the best fitting principal components.