Interaction between aberrations to improve or reduce visual performance

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Purpose: To investigate how pairs of Zernike modes interact to increase or decrease visual acuity.

Setting: Visual Optics Institute, College of Optometry, University of Houston, Houston, Texas, USA.

Methods: Subjects read aberrated and unaberrated visual acuity charts 3 times. Each aberrated chart was produced by convolving an aberrated point-spread function with an unaberrated acuity chart. Point-spread functions were defined by 4 pairs of Zernike modes. For each pair, 9 combinations were used, ranging from all aberration being loaded into the first mode to all aberration being loaded into the second mode. The root mean square (RMS) wavefront error always totaled 0.25 μm (6.0 mm pupil), a level similar to the aberration induced by traditional flying small-spot laser refractive surgeries.

Results: For all conditions (except the unaberrated charts), visual acuity decreased. Acuity varied significantly depending on which modes were mixed and the relative contribution of each mode. Modes 2 radial orders apart and having the same sign and angular frequency tended to combine to increase visual acuity. Modes within the same radial order tended to combine to decrease acuity.

Conclusions: For low levels of aberration, the RMS wavefront error is not a good predictor of visual acuity. Clinically, it is important to define how aberrations interact to optimize visual performance. New metrics of optical/neural performance that correlate better with clinical measures of visual performance need to be adopted or developed, as well as new clinically viable measures of visual performance that are sensitive to subtle changes in optical performance.

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Retinal image quality is degraded by scatter, diffraction, and wavefront aberrations (better known as wavefront errors). In healthy eyes with pupils larger than 3.0 mm and minimal cataract formation, the wavefront error is the main contributor to image degradation. The use of wavefront sensors and the Zernike expansion (Figure 1) to describe the wavefront error of the eye is an accepted measurement in research and is becoming accepted in leading clinical practices. The reasons are straightforward. Measurement of the wavefront error of the eye provides an accurate method to (1) assess the optical properties of the eye beyond sphere and cylinder, (2) evaluate therapy (eg, refractive surgery) designed to improve the optical properties of the eye, and (3) provide the necessary information to design optical prescriptions for the eye to minimize all refractive errors.

One advantage of using the normalized Zernike expansion to describe ocular aberration is that the value of each mode's coefficient represents the root mean square (RMS) wavefront error attributable to that mode.[1–3] Because these modes can be mathematically described independently of one another, higher-value coefficients identify the mode or modes having the

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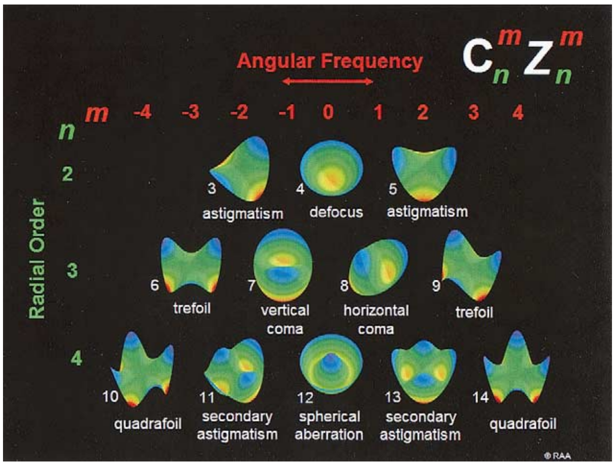

Figure 1. (Applegate) Zernike expansion showing the 2nd, 3rd, and 4th radial order modes using the Optical Society of America (OSA) recommended notation.[1–3] In the expression $C_n^m Z_n^m$ located in the upper right-hand corner of the figure, the *n* refers to the radial order and the *m*, to the angular frequency of each specific coefficient (C_n^m) and mode (Z_n^m) of the Zernike expansion. The coefficient defines how much of each individual mode contributes to the total wavefront error. Mathematical representation of the Zernike expansion through the 7th radial order for describing ocular wavefront error (ocular aberration) has been published.[1–3] In this paper, all values are coefficient values. For the first 4 radial orders, names have been assigned to each mode, as seen here. However, beyond the 4th radial order, naming becomes less intuitive. For this reason, the recommended OSA double index notation is used.

greatest impact on the total RMS wavefront error of the eye. However, mathematical independence of the modes does not mean their impact on visual performance is independent.

To date, the focus has been on aberration measurement and reduction primarily through adaptive optics in research[4,5] and refractive surgery in the clinic.[6–8] Little attention has been devoted to the relation between aberration and visual performance. Instead, it has been tacitly assumed that as aberration increases, visual performance decreases. This assumption is not unreasonable. Earlier work[9] correlating measurements of corneal aberrations, expressed as log wavefront variance to the area under the log contrast sensitivity function ($r^2 = 0.53$) and the square root of wavefront variance to high- and low-contrast logMAR visual acuity ($r^2 = 0.45$ and $r^2 = 0.46$, respectively), supports this assumption. An advantage and limitation of this data set is that the range of aberrations and acuities was purposely high. That is, the data set included patients having keratoconus, penetrating keratoplasty, and ocular trauma as well as normal eyes and refractive surgery patients. Over a large range of aberrations, the correlation between the ocular RMS wavefront error and measures of visual performance is reasonably good.

An important aspect of refractive surgery is the correlation between ocular aberration and measures of visual performance over the smaller range of aberration that occurs in normal and refractive surgery patients. Limiting the data set of previous work[9] to normal and refractive surgery patients revealed a much lower correlation. Supporting this observation, Hong et al.[10] found that only a small part of the variance in visual performance of normal optometry students could be accounted for by a variation in the RMS wavefront error.

Why is the correlation between aberration and visual performance so poor in the low ocular aberration range? Perhaps the most important reason for the decrease in correlation is attributable to the variation in the neural transfer function across subjects; that is, variations across individuals in how well the retinal image is transduced and interpreted by the neural portion of the visual system. From a clinical treatment standpoint, it is not as important to know how visual performance varies across individuals as it is to know how a given individual responds to a change in aberration structure (eg, as is induced by refractive surgery).

Another reason for the low correlation between low levels of RMS error and visual performance is that common clinical measures of visual function (eg, high-contrast visual acuity) are not particularly sensitive to low levels of aberration, particularly when acuity is scored to the line (eg, 20/20) as opposed to the letter.[11] This point is worth emphasizing; the sensitivity of high-contrast visual acuity tests can be increased by counting all letters read correctly until a set number of letters (typically 5) are missed and converting the total number of letters read correctly to a visual acuity score.[12] Yet another reason is that all aberrations are not equal.[13] It has been demonstrated that each mode of the Zernike expansion has a different impact on visual performance as measured by high- and low-contrast acuity. This last example is seen clinically when a cylindrical lens is rotated in front of a corrected eye or when an uncorrected eye views a fan dial. Depending on the orientation of the axis of the cylindrical error, various spokes of the fan dial will appear clearer. Similarly, various letters will appear clearer depending on the stroke orientation of the letter.

Finally, it has been demonstrated that 1 aberration can be used to balance another and improve the modulation transfer function (MTF) and subsequent image quality.[14–16] In this paper, we explore the positive and negative impacts of these effects on letter acuity by keeping the total RMS error constant and mixing various proportions of 2 Zernike modes.

In discussing their earlier work, Applegate and coauthors[13] noted that when combined, Zernike modes can increase or decrease visual performance. Specifically, they noted that when combined, these modes can interact to improve acuity despite an increase in the total wavefront error. For example, spherical aberration and defocus can be combined so that the individual modes affect vision more than the combination. The authors stated that Zernike modes with like signed coefficients 2 radial orders apart (eg, radial orders 2 and 4) and having the same angular frequency (eg, angular frequencies 0, –2, or 2) can be combined so that the effect on acuity is less deleterious than the individual effects. The rationale for this effect can be visualized by noting that these combinations, when in correct proportions, decrease the wavefront error over the center of the pupil (Figure 2), where light is most efficient in eliciting a visual response.[17,18] We have completed studies to support these observations and report our findings here.

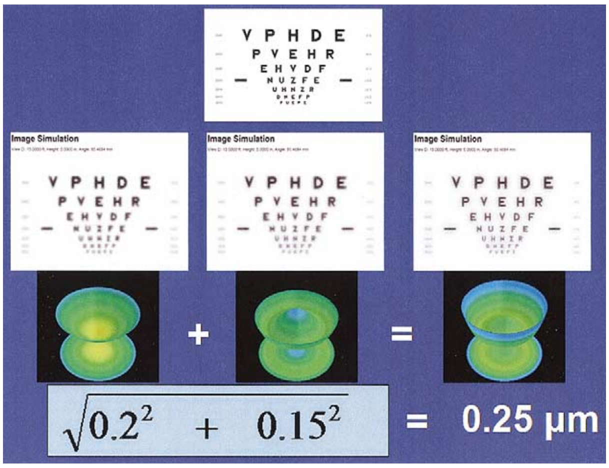

Figure 2. (Applegate) *First row*: An aberration-free chart. *Second row*: Simulations of the visual impact of 0.20 µm of RMS error loaded into defocus (C_2^0) alone, the test condition of $C_4^0 = 0.15$ µm alone, and the combination ($C_2^0 + C_4^0$), totaling 0.25 µm RMS error. Note that even though there is less RMS error in the defocus and spherical aberration conditions, the acuity image quality is worse than the combination in which the RMS error is larger. Furthermore, even though the combination provides a better image, it is not better than having no aberration. The acuity line marked with a bar corresponds to the 20/20 line. *Third row*: Corresponding 3-D wavefront-error maps.

The normalized Zernike expansion makes it possible to decompose the wavefront error into individual error modes. The total wavefront error can then be expressed as a linear combination of error modes, defined as Z_n^m, where n is the radial order and m is the angular frequency (Figure 1). In the following experiments, we varied the coefficients of specific pairs of modes, keeping the total amount of RMS wavefront error constant.

Subjects and Methods

Three subjects, aged 23, 26, and 52 years, participated in this study. All were free of ocular pathology and had a best corrected visual acuity of at least 20/16.

Generation of Acuity Charts

CTView computer software, version 4.15 (Sarver and Associates, Inc.), was used to create aberrated charts by convolving the aberrated point-spread function of the desired combined Zernike modes for a 6.0 mm pupil with an unaberrated letter chart. These methods are nearly identical to the earlier work of Burton and Haig[19] published in 1984 in which the effects of the Seidel aberrations were simulated on a screen and viewed through a small artificial pupil. Each CTView logMAR chart generated consisted of randomly selected letters from an equally identifiable letter set calibrated for a 10-foot test distance. Steps between acuity lines were the standard 0.1 logMAR. Acuity charts were printed using a high-resolution (600 dpi) printer on 8.5 inch × 11 inch photographic-grade paper. Individual chart aberrations were induced by paired Zernike modes from the 2nd and 4th radial orders.

Four pairs of Zernike modes were studied: $C_2^0 + C_4^0$ (defocus and spherical aberration), $C_2^{-2} + C_4^{-2}$ (astigmatism and secondary astigmatism), $C_4^0 + C_4^{-4}$ (spherical aberration and quadrafoil), and $C_4^0 + C_4^{-2}$ (spherical aberration and secondary astigmatism). These represent a small subset of the possible combinations of Zernike modes. They were chosen based on preliminary observations suggesting that $C_2^0 + C_4^0$ and $C_2^{-2} + C_4^{-2}$ will combine to increase visual acuity[13] relative to either component separately; $C_4^0 + C_4^{-4}$ and $C_4^0 + C_4^{-2}$ will combine to decrease visual acuity relative to either component separately. Table 1 shows the 9 test combinations for Zernike coefficients C_2^0 and C_4^0 totaling an RMS error of 0.25 µm over a 6.0 mm pupil (equivalent of 0.19 diopter [D]). The same coefficient values were used with $C_2^{-2} + C_4^{-2}$, $C_4^0 + C_4^{-2}$, and $C_4^0 + C_4^{-4}$ pairings, yielding a total of 36 aberrated chart conditions. An additional 3 unaberrated test charts were added to the 36 aberrated charts to serve as a normalization reference. Thus, in total, 39 individual acuity charts were used.

A constant amount of RMS error (0.25 μm) was chosen because when loaded into the defocus mode (C_4^0), acuity decreases an average of 8 letters (from 20/15$^+$ to 20/20$^-$) on high-contrast logMAR acuity charts.[13] This range of acuity (20/20$^-$) is generally considered a reasonable lower limit of good refractive surgery outcomes. The total RMS error is calculated by taking the square root of the sum of the squared Zernike coefficients. An example of a calculation is shown in Figure 3.

Protocol

The protocol used was similar to that in other works.[13,20] In summary, each subject had 1 pupil dilated and accommodation paralyzed with cyclopentolate hydrochloride 1%. The test eye was positioned 14.5 mm behind a 3.0 mm artificial pupil, and the fellow eye was occluded. The test eye's dilated pupil was centered on the 3.0 mm artificial pupil using a foveal achromatic alignicator[21–23] (a device to provide a good estimate of the foveal achromatic axis) and maintained in position using a bite bar attached to a 3-dimensional (3-D) translator.

A 3.0 mm artificial pupil was used because it optimizes the normal eye's optical quality by balancing diffraction effects that result with smaller pupils and higher-order aberrations that are passed with larger pupils.[24] Although the physical pupil chosen was 3.0 mm, the charts were aberrated in CTView using a 6.0 mm pupil. One can examine the impact of 0.25 μm of the RMS error produced in an acuity chart over a 6.0 mm pupil with minimal loss in fidelity through a 3.0 mm artificial pupil because the aberrations contained in the chart image so decrease the MTF that the majority of the relevant spatial information contained in the aberrated chart will pass through the 3.0 mm artificial pupil into the eye.[13] Equally important, the spatial filtering caused by a 3.0 mm pupil and the residual ocular aberration are constant for all test conditions for each subject. Together, these factors minimize the adverse impact of residual aberrations and diffraction on experimental measurements.

Subjects were optimally refracted through the 3.0 mm pupil for a 10-foot test distance. They read each of the 39 high-contrast logMAR charts monocularly until 5 letters were missed. Acuity was defined for each chart as the total letters correct up to the 5th miss. Acuity for the set of 39 charts was measured 3 times for each subject. Chart illumination was maintained at 100 cd/m^2.

Table 1. Test conditions for $C_2^0 + C_4^0$.

Condition	C_2^0 (μm)	C_4^0 (μm)
1	0.000	0.250
2	0.050	0.245
3	0.100	0.229
4	0.150	0.200
5	0.177	0.177
6	0.200	0.150
7	0.229	0.100
8	0.245	0.050
9	0.250	0.000

Normalization and Averaging

To allow comparison across subjects, each subjects' data were normalized as follows:

$$L = LC(A) - \overline{LC}(UA) \tag{1}$$

where L is letters lost (negative) or gained (positive), $LC(A)$ is letters correctly read on the aberrated chart, and $\overline{LC}(UA)$ is the average letters correctly read on 3 unaberrated control charts.

In this normalization, negative numbers correspond to a decrease in acuity. Normalized data for each subject's 3 trials were then averaged for each test condition. These means were averaged across subjects to obtain the mean of means and the standard deviation (SD) of the means for each test condition.

Results

Figure 4 shows that all combinations of C_2^0 (defocus) and C_4^0 (spherical aberration) decrease visual performance. That is, there is no combination of C_2^0 and C_4^0 that improves acuity compared to the unaberrated condition. Second, Figure 4 shows an increase in visual performance for all combinations of C_2^0 and C_4^0 (solid symbols) over that of loading the same amount of aberration solely in C_2^0 or C_4^0 (open symbols). The peak improvement in the test conditions occurs when $C_2^0 = 0.20$ μm and $C_4^0 = 0.15$ μm with an improvement of ≈ 8 letters, or nearly 2 lines (10 letters) on a standard logMAR acuity chart when compared to C_2^0 or C_4^0 alone (open symbols). The improvement in visual acuity over loading the entire error into C_2^0 or C_4^0 was significant ($P = .001$ and $P = .003$, respectively, paired *t* test).

As with $C_2^0 + C_4^0$, all combinations of astigmatism (C_2^{-2}) and secondary astigmatism (C_4^{-2}) reduced acuity when compared to the unaberrated control conditions. Astigmatism (C_2^{-2}) by itself decreased acuity less than secondary astigmatism (C_4^{-2}). Figure 5 follows a similar trend as the C_2^0, C_4^0 combinations (Figure 4), peaking when $C_2^{-2} = 0.229$ μm and $C_4^{-2} = 0.10$ μm. The

Calculation of RMS error: $\sqrt{(C_2^0)^2 + (C_4^0)^2} = \mathrm{RMS}(C_{\mathrm{total}})$

Example for condition 3, Table 1: $\sqrt{0.20^2 + 0.15^2} = 0.25\,\mu\mathrm{m}$

Figure 3. (Applegate) Demonstration of a total RMS calculation if $C_2^0 = 0.20$ and $C_4^0 = 0.15$ and all other modes have no aberration. The resulting total RMS is 0.25 μm. All aberrated charts were generated using a total RMS of 0.25 μm over a 6.0 mm pupil (spherical equivalent 0.19 D).

overall visual improvement is ≈3 letters when compared to $C_2^{-2} = 0.25$ μm ($P = .050$, paired *t* test) and ≈7 letters when compared to $C_4^{-2} = 0.25$ μm ($P = .041$, paired *t* test).

Figures 6 and 7 show letters lost in cases in which the RMS error is combined within the same (4th) radial order. For the spherical aberration (C_4^0) + quadrafoil (C_4^{-4}) pairing (Figure 6), visual performance decreased for all test conditions compared to loading the total error into C_4^{-4}. Loading all the RMS error into the spherical aberration (C_4^0) reduced visual acuity more than loading all the error into the quadrafoil (C_4^{-4}) (Figure 6). The maximum variation between conditions was on the order of 5 letters or 1 line. The maximum loss in letters read for the combination ($C_4^0 = 0.20$, $C_4^{-4} = 0.15$) was significantly larger than the loss that occurred from loading the entire error into C_4^0 or C_4^{-4} ($P = .029$ and $P = .04$, respectively). For the spherical aberration (C_4^0) and secondary astigmatism (C_4^{-2}) pairing (Figure 7), the impact of varying the relative contributions of each mode did not have a systematic effect. The biggest difference between means was on the order of 5 letters (1 line of acuity).

Discussion

A goal of wavefront-guided refractive surgery is to improve visual performance by minimizing the RMS error. Reducing the optical aberrations to zero over a large pupil will provide the best retinal image; however, such an accomplishment is not realistic or achievable. A near-term goal of refractive surgery is to not induce a new aberration while correcting the sphere and astigmatism modes (second radial order modes C_2^{-2} [astigmatism], C_2^0 [defocus], C_2^2 [astigmatism]), and a longer-range goal is to routinely minimize existing higher-order aberrations.

Traditional and wavefront-guided refractive surgeries reduce the magnitude of 2nd-order wavefront errors (sphere and cylinder). Accompanying this reduction in traditional refractive surgeries is an increase in higher-order aberrations, usually in the form of coma and spherical aberration.[25] Recent U.S. Food and Drug Administration submission data using wavefront-guided flying-spot laser corneal surgery using the Alcon CustomCornea® system show that induced aberrations are about one half the magnitude of traditional surgery,

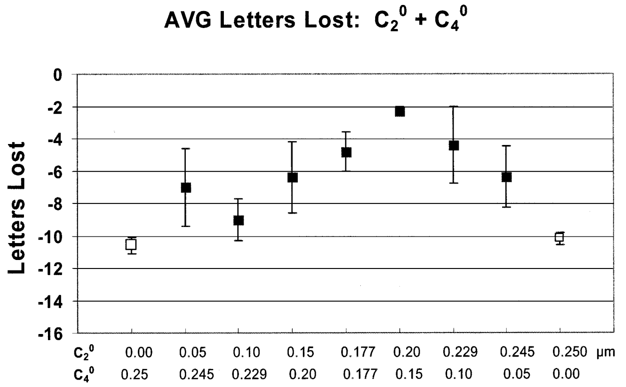

Figure 4. (Applegate) Average letters lost across subjects as a function of various combinations (solid symbols) of defocus (C_2^0) and spherical aberration (C_4^0) that result in a constant total RMS error of 0.25 μm. Open symbols at each end represent 0.25 μm loaded into each single mode. Error bars equal ±1 SD.

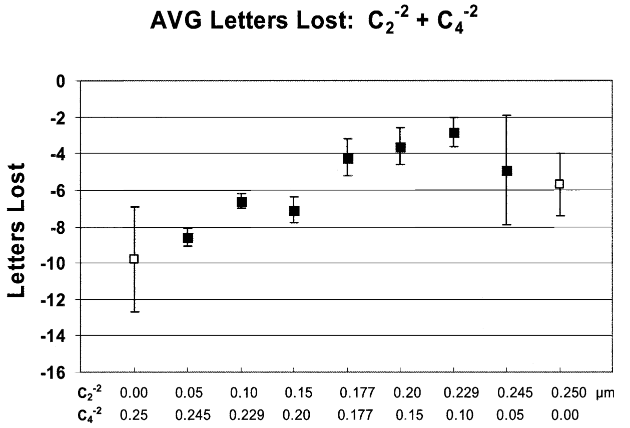

Figure 5. (Applegate) Average letters lost across subjects as a function of various combinations (solid symbols) of astigmatism (C_2^{-2}) and secondary astigmatism (C_4^{-2}) that result in a constant total RMS error of 0.25 μm. Open symbols at each end represent 0.25 μm loaded into each single mode. Error bars equal ±1 SD.

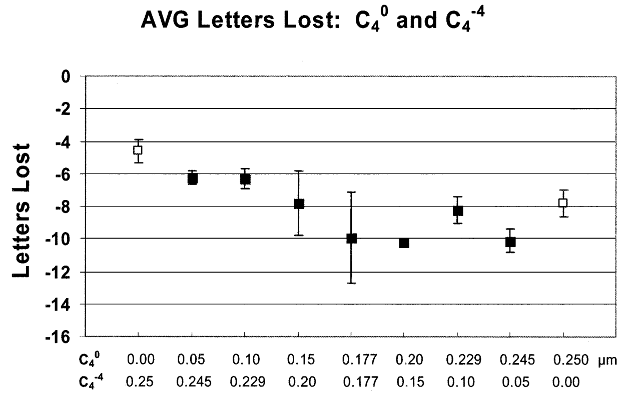

Figure 6. (Applegate) Average letters lost across subjects as a function of various combinations (solid symbols) of spherical aberration (C_4^0) and quadrafoil (C_4^{-4}) that result in a constant total RMS error of 0.25 μm. Open symbols at each end represent 0.25 μm loaded into each single mode. Error bars equal ±1 SD. Note that the chart in this experiment that has 0.25 μm RMS spherical aberration contains a different set of letters than the 0.25 μm RMS spherical aberration chart used in Figure 4. Thus, a comparison of the letters lost in the experimental results displayed in Figures 6 and 4 for a 0.25 μm RMS error in spherical aberration provides an estimate of experimental variability in data collection.

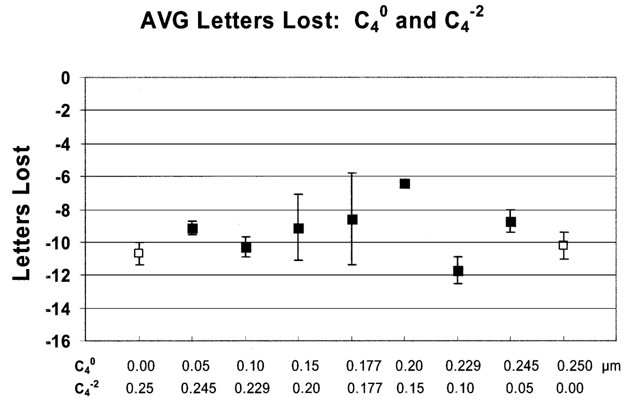

Figure 7. (Applegate) Average letters lost across subjects as a function of various combinations (solid symbols) of spherical aberration (C_4^0) and secondary astigmatism (C_4^{-2}) that result in a constant total RMS error of 0.25 μm. Open symbols at each end represent 0.25 μm loaded into each single mode. Error bars equal ±1 SD.

with an associated increase in the number of eyes achieving 20/15 or better acuity. Studies by Alcon investigators found that approximately 30% of eyes have higher-order aberrations that are less than presurgical levels (S. Brint, MD, "Wavefront Guided Custom Cornea for Correction of Previously Operated Eyes: Case Studies," presented at the 2002 International Society of Refractive Surgery, Orlando, Florida, USA, October 2002).

Although such results are encouraging for all in the industry, as long as wavefront-guided corrections leave significant amounts of aberration, understanding how residual aberrations interact to affect visual function will be important in optimizing visual outcomes. Said differently, given that aberration is being induced or not entirely eliminated by refractive surgery, the adverse effect of the aberration can be minimized by avoiding aberration near the center of the Zernike tree (eg, coma, spherical aberration, and, especially, secondary astigmatism)[13] and by minimizing the combinations of aberration that decrease visual performance in favor of combinations that increase visual performance, as reported here.

An important advantage of the normalized Zernike notation is that the coefficient for each mode reveals the relative contribution of each mode to the total RMS error. This study and earlier work[13] demonstrate that the RMS error at magnitudes typically induced by refractive surgery is not a good predictor of visual acuity. That is, in all the conditions reported in this study and in previous work,[13] the RMS was a constant 0.25 μm (a constant equivalent defocus of 0.19 D), yet visual acuity varied markedly (up to nearly 2 lines on a high-contrast logMAR chart).

So what metrics of optical quality might better correlate with visual performance? We do not have a definitive answer but do have several directions we are pursuing. Insight into some of our thinking can be gained by inspecting how the wavefront error is distributed across the pupil. It is our contention that the greater the area in the center of the pupil over which the wavefront error is reasonably flat, the better the visual acuity. This principle can be seen by observing plots of the wavefront error of C_2^0 (defocus) and C_4^0 (spherical aberration) alone and together (Figure 2). When the defocus (C_2^0) is added to the spherical aberration (C_4^0) in the right proportions, the peak-to-valley wavefront error in the center of the pupil is markedly reduced. In the simulations in Figure 2, the optical quality of visual acuity charts varies considerably and none of the aberrated simulations are as good as those on the unaberrated chart. In addition, the quality of the chart can be diminished significantly, yet the letters can still be identified correctly. This observation is consistent with the relatively common patient comment, "I can read 20/20 but it is not as good as it used to be."[13] Furthermore, it is clear from this demonstration that visual performance depends on how the residual wavefront error is distributed across Zernike modes.

We are just beginning to quantitatively explore the relationship between the flatness of the wavefront in the center of the pupil and visual performance but are approaching the problem by slowly opening the pupil and repeatedly calculating the wavefront error until a criterion is met. We suspect that the larger the pupil when the criterion is reached, the better the acuity.

A more traditional measure of optical performance in the spatial domain is the Strehl ratio, defined as the ratio of the light at the peak of the diffraction pattern of an aberrated image to that at the peak of an aberration-free image.[26] The Strehl ratio is generally thought to be a good metric for nearly aberration-free systems. Therefore, perhaps as refractive interventions get closer to rendering the eye diffraction limited, the Strehl ratio will prove to be a good predictive measure of visual performance. To begin to test this hypothesis, we plotted the Strehl ratio for each of our test conditions in the C_2^{-2} + C_4^{-2} condition and the C_4^0 + C_4^{-4} condition to see whether the form of the function follows our visual acuity results (Figures 8 and 9). These results are encouraging in that the Strehl ratio is the largest for the combination of Zernike modes that provide the best visual acuity, suggesting that the ratio may be predictive when the total RMS is relatively low.

It is anticipated that differential effects of individual aberrations and combinations of aberrations will explain why normal eyes and refractive surgical eyes with similar or different residual RMS wavefront error have similar or different visual acuities. Consider the following 3 refractive surgical results: First is a relative young patient (one who can accommodate easily) who had traditional refractive surgery and was left with a considerable amount of positive spherical aberration over the physiologic pupil. This patient can add a small amount of myopic defocus by accommodating to minimize the adverse effects of the positive spherical aberration and thus improve visual performance. Second is a patient individual who was left with the same total amount of RMS error loaded into horizontal coma, secondary astigmatism, or a combination that was particularly bad for visual performance that cannot be mitigated by adjusting accommodation. Third is a 43 year old with the same surgical outcome as the first patient. As this individual ages and loses the ability to accommodate and offset some of the consequences of the high positive spherical aberration, vision will decrease.

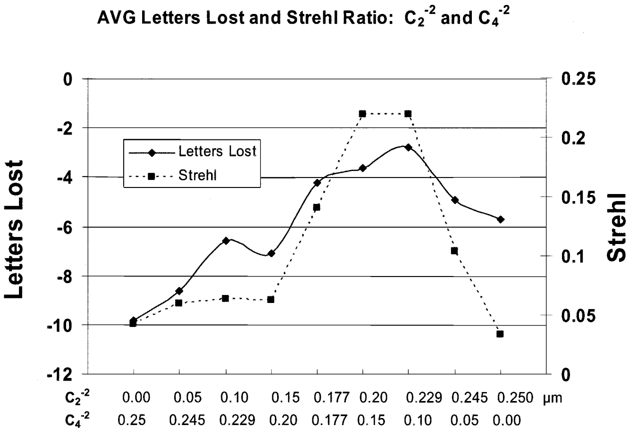

Figure 8. (Applegate) Strehl ratio and letters lost for combinations of astigmatism (C_2^{-2}) and secondary astigmatism (C_4^{-2}).

We are working with Larry Thibos, PhD, Indiana University, and David Williams, PhD, University of Rochester, using more than 20 traditional optical metrics (eg, half height at half width, correlation width of light distribution, standard deviation of light distribution) and new optical metrics to see which best accounts for our experimental result. It is likely that traditional optical metrics will not be entirely adequate to explain the result. The reason is that the optics of the eye are 1 stage of the visual system. New metrics that include the impact of the individual's neural transfer function and optical transfer function will likely best predict actual

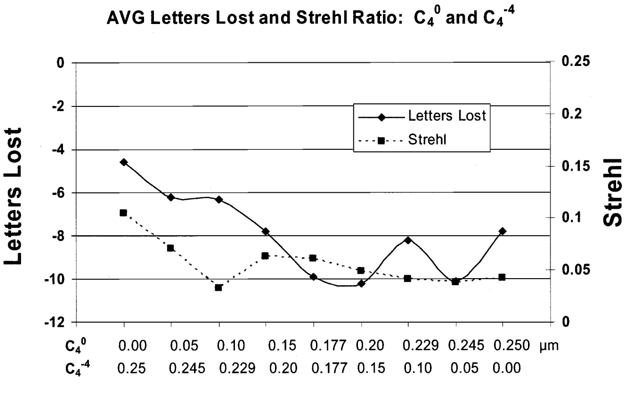

Figure 9. (Applegate) Strehl ratio and letters lost for combinations of spherical aberration (C_4^0) and quadrafoil (C_4^{-4}).

visual performance. The neural transfer function defines modulation loss as a function of spatial frequency caused by converting the retinal image to neural impulses and transferring the information through to the neural system and out as a percept. The final percept is based on the quality of the retinal image formed by the optics of the eye and the quality of the neural transfer of this information into a percept.

Equally important in developing predictive metrics of visual performance is the visual performance task one wants to predict. It is anticipated that different metrics of optical–neural performance may perform better for different visual tasks. Here, we explored the impact on high-contrast visual acuity because high-contrast letter acuity is the world standard for measuring visual performance. Nonetheless, different metrics of optical performance will probably need to be developed for other important visual tasks, such as face recognition, for which a lower band of spatial frequencies is critically important.

Conclusion

In conclusion, for a constant low level of RMS wavefront error (0.25 μm over a 6.0 mm pupil, a constant level of equivalent defocus equal to 0.19 D), visual acuity varies significantly depending on which Zernike modes are participating and their relative contributions. The RMS wavefront error and equivalent defocus are not good predictors of visual performance for low levels of optical aberration in the range of typical good refractive surgery outcomes. Modes 2 radial orders apart (eg, radial orders 2 and 4) in the Zernike expansion and that have the same angular frequency (eg, angular frequency 0, –2, or 2) can be combined to improve visual acuity. Modes within the 4th Zernike radial order generally combine to decrease acuity.

Clinically, it is important to define how Zernike modes interact in an effort to optimize visual performance following procedures designed to reduce the optical aberrations of the eye (eg, wavefront-guided refractive surgery, intraocular lenses, and contact lenses). New metrics of optical–neural performance that correlate better to clinical measures of visual performance and new metrics of visual performance that are more sensitive to small changes in optical quality must be developed.

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