

Wavefront aberrations and spectacle lenses

part one

In response to requests for more challenging CET, Darryl Meister ABOM, explains the fundamentals of wavefront aberrations and image quality in part one of this two-part series

Competences covered:
Target group:

Optical appliances
Dispensing opticians, optometrists

Although evaluating the 'wavefront' aberrations of a lens or optical system has become commonplace in fields such as astronomy, in which adaptive optical systems minimise the wavefront aberrations of telescopes caused by atmospheric turbulence, there is increasing interest in the ophthalmic applications of this technology. This interest has been driven in no small part by recent advances in laser refractive surgery that in theory could allow surgeons to reduce the 'high-order' wavefront aberrations of the eye, in addition to the traditional spherical and cylindrical refractive errors, using a procedure known as wavefront-guided ablation. Eliminating the high-order aberrations of the eye may allow us to achieve *supernormal* vision, with better than 'normal' visual acuity and contrast sensitivity'.

Wavefront aberrations

The propagation of 'light' has been described as a rapid movement of energy particles (photons) that travel in a wave-like manner. The propagation of light from an object

point can be represented theoretically using rays emanating outward from the object or waves emanating outward that are perpendicular to those rays. Just as rays of light diverge from an object point, waves of light spread out like ripples of water travelling away from a stone that has been dropped into a pond. At any given distance from the original object point, a *wavefront* exists that represents the envelope bounding waves of light that have travelled an equal distance from the object.

As the distance from the object increases, the curvature of these wavefronts becomes progressively flatter, eventually appearing flat beyond 'optical infinity'. The object point serves as the common centre of curvature of these wavefronts (**Figure 1**). Conversely, light converging to a point focus can be described using spherical wavefronts that become progressively smaller, converging to an infinitely small image point. Further, a ray of light from the same object point remains perpendicular to the

corresponding wavefront as both propagate away from the object or toward the image.

Aberrations are focusing errors that prohibit proper image formation. There are several ways to characterise the aberrations produced by a lens or optical system. In geometrical optics, ray tracing is often utilised to calculate the path of a bundle of rays from an object point as the rays are refracted at the various surfaces of each lens or optical element. Aberrations are then determined by calculating the distance of these refracted rays from the intended focal point. Alternatively, the deformation of the corresponding wavefront of light as it passes through the optical system may be also determined.

In a perfect optical system, spherical wavefronts of light from an object point should converge to a single point focus at the desired image location, such as the retina of the eye. In the presence of optical aberrations, however, these wavefronts become



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either too steep, too flat, or distorted from their ideal shape (Figure 2). Accordingly, rays of light corresponding to these wavefronts are spread out or smeared at the plane of the desired focus by these aberrations, instead of intersecting at a single, sharp point.

Wavefront aberrations represent a convenient way to characterise complex optical errors in focus produced by an optical system. At any point across the aperture of the optical system, such as the pupil of the eye, the wavefront error is the effective optical separation, or difference in *optical path length*, between the actual aberrated wavefront and the ideal reference wavefront. These errors are usually expressed in micrometres or microns (μm), which are equal to one-thousandth of a millimetre (0.001mm).

For a given object point, the overall shape of the wavefront aberration after it has been refracted by the optical system can be modelled and quantified mathematically, if a sufficient number of wavefront error measurements are taken across the aperture of the system. The shape of an aberrated wavefront can be modelled from wavefront error measurements by 'fitting'—or closely approximating—the measurements with a series of polynomials. Using mathematical curve fitting techniques, the measurement data is 'expanded' or expressed as a sum of terms of polynomial functions. Increasing the number of terms used in these polynomials results in successively more accurate approximations of the original wavefront. The most common polynomial series in ophthalmic use is the *Zernike polynomial series*, which has been shown to characterise the optical aberrations of the eye effectively².

Zernike polynomial series

The Zernike polynomial series is used to breakdown or decompose complex wavefronts into a collection of polynomial basis functions called modes. These basis functions allow the shape of even complex wavefronts to be broken down, or decomposed, into an assortment of more basic component shapes. Just as you can reconstruct a model of a house by combining various simple shapes, such as triangles and rectangles, you can also reconstruct a given wavefront from an appropriate combination of

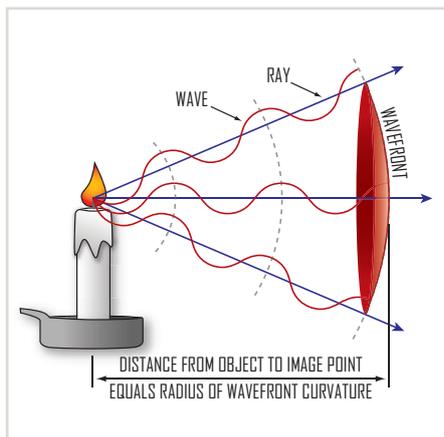


Figure 1: A wavefront represents the envelope that bounds waves of light at a given distance from an object point or an image point

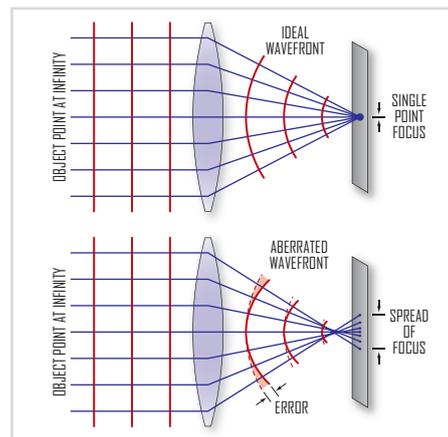


Figure 2: In the presence of optical aberrations, wavefronts of light do not converge to a sharp point focus at the desired image plane

these fundamental shapes or modes (Figure 3).

Further, each Zernike mode is associated with a particular type of optical error, or wavefront aberration, allowing the wavefront errors to be described as a combination of quantities of more basic optical aberrations that are also more familiar to eye care professionals. Each Zernike mode includes two components:

1. The *radial order* component indicates the exponential variation of the polynomial function away from the centre of the pupil—or how many peaks and troughs occur away from the centre.
2. The *meridional frequency* component indicates the number of sinusoidal repetitions of the function around the meridians of the pupil—or how often the peaks and troughs repeat around the circumference.

Zernike aberration modes are commonly represented using a double indexing scheme:

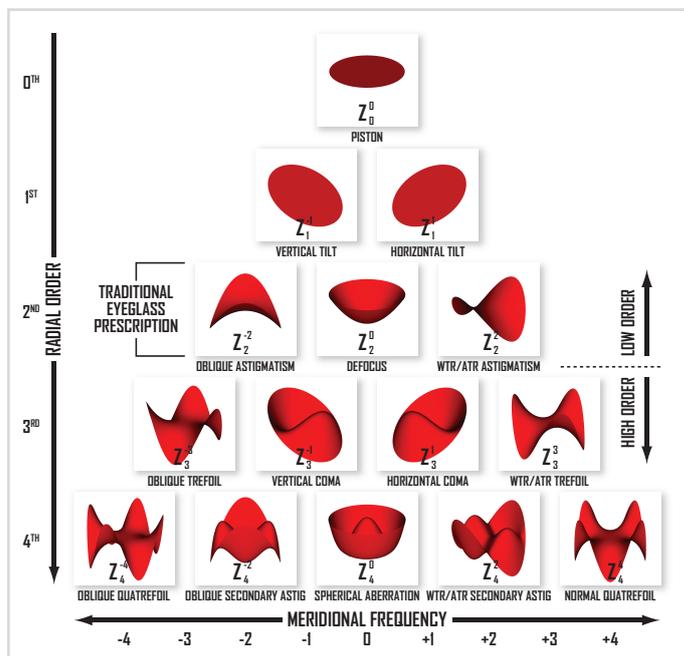
$$Z_n^m$$

where n is a whole number indicating the radial order and m is a positive or negative integer indicating the meridional frequency of the mode. For instance, the polynomial function of the Zernike mode expressed as Z_3^1 , varies as a cubic function away the centre of the pupil ($n = 3$) and varies sinusoidally one time around the circumference of the pupil ($m = 1$).

Zernike aberration modes are commonly grouped by their radial order (n), which indicates how much the contribution of a given range of modes to the overall shape of the wavefront depends upon pupil size. Each radial order contains one or

Continued overleaf

Figure 3: Displaying the Zernike polynomial functions by their radial order produces a pyramid of aberration modes (modes to the fourth order have been shown)



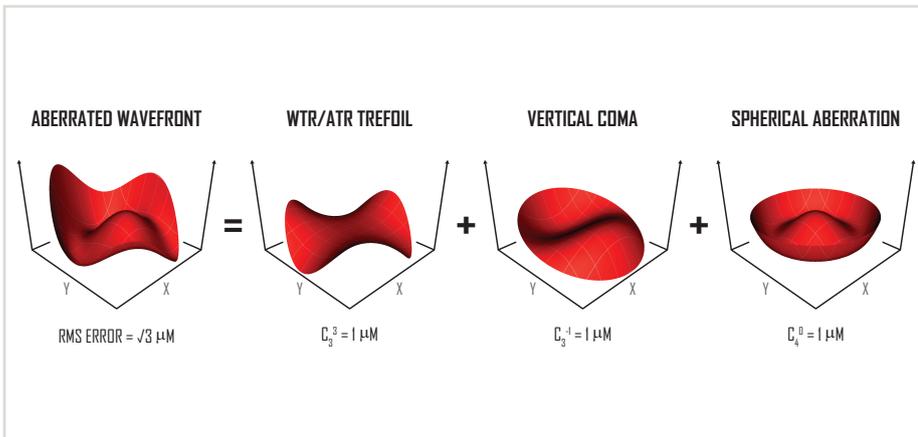


Figure 4: Even complex wavefront shapes can be 'decomposed' into a combination of more fundamental aberrations

more aberration modes, each with a specific meridional frequency (m). The radial orders of the Zernike polynomial series increase indefinitely. The number of modes within each radial order also increases as the radial order increases from the addition of modes with successively higher meridional frequencies, resulting in a pyramid of aberration modes when the Zernike polynomial series is represented graphically (**Figure 3**).

The Zernike polynomial basis function varies as a function of the *sine* of the angle formed by each meridian of the pupil when m is negative and as a function of the *cosine* of the angle when m is positive. Consequently, modes in the same radial order with meridional frequencies that are equal in value but opposite in sign (Z_n^{-m} and Z_n^{+m}) represent the same shape but are rotated with respect to each other. This allows aberration modes with vertical and horizontal components (such as prism) or oblique and with-the-rule/against-the-rule components (such as astigmatism) to be represented unambiguously. Modes with a meridional frequency of zero ($m = 0$) have polynomial functions that do not vary around the circumference of the pupil, resulting in a rotationally symmetrical shape.

Of particular interest are the three Zernike aberration modes of the second radial order ($n = 2$), known collectively as the *second-order* aberrations. This radial order corresponds to the traditional curvature or vergence of the wavefront. The centre mode (Z_2^0), referred to as defocus, has the shape of a paraboloid and corresponds with the average sphere power error of the wavefront.

The outer two second-order modes (Z_2^{-2} and Z_2^{+2}), referred to as *astigmatism*, have the shape of a capstan toric surface and correspond to the *cylinder* power error of the wavefront. This capstan shape has positive refractive power through one principal meridian and negative refractive power of the same magnitude through the other meridian, resulting in a *spherical equivalent*—or average power—equal to zero, similar to a Jackson cross-cylinder. A cylinder axis is not specified separately, so two cylinder components—indicating the amount of cylinder power present at either axis 45 or axis 135 and at either axis 180 (with-the-rule) or axis 90 (against-the-rule)—are required to define the power and orientation of the cylinder power. The total cylinder power is equal to the vector sum of these two components.

Each Zernike aberration mode also has a coefficient C_n^m associated with it, which indicates the amount of that particular Zernike aberration mode present in the actual wavefront at a given aperture or pupil size. Essentially, each coefficient serves as a scaling factor that sets the size—or heights of the peaks and troughs—of the polynomial function of the corresponding Zernike aberration mode. This 'decomposes' a complex wavefront shape into specific quantities of individual aberration modes (**Figure 4**). These coefficients are ordinarily determined by fitting the wavefront error measurements with each Zernike polynomial using a least-squares method.

Zernike polynomial functions are *orthogonal*—or independent of each other—over a circular pupil. Each Zernike polynomial is also 'balanced'

with polynomial terms of lower or equal order to minimize the variance of the Zernike polynomial. These features result in some useful properties³:

- The contribution of an individual Zernike aberration mode to the total wavefront error is given by the magnitude of its corresponding coefficient.
- The variance of each aberration mode is given by the square of its corresponding coefficient.
- The total variance of the wavefront is equal to the sum of the variances of the individual aberration modes.
- The addition of more Zernike aberration modes can only increase the total wavefront error.
- Adding higher-order Zernike aberration modes will not alter the lower-order modes.
- Eliminating wavefront aberrations up to a given radial order will minimise the total error of the aberrated wavefront up to that order.

Wavefront aberrations and image quality

In the absence of optical aberrations, the image quality of an optical system is limited by *diffraction*, which is the subtle bending or spreading of light at the edge of an aperture. Instead of reproducing a point of light from an object as an equally sharp and equally intense image point, diffraction results in a slight diffusion of the focus. When the aperture is circular, as is the case with the pupil of the eye, diffraction produces a circular pattern known as *Airy pattern*, which is characterised by a central disk of maximum of image intensity, surrounded by rings of significantly lower intensity (**Figure 5**). Diffraction varies inversely with pupil size, increasing as the pupil size becomes smaller.

Visual acuity is the most common *subjective* measure of image quality in eye care. *Visual acuity* represents the resolving power of the eye or the ability to discriminate two object points as separate. Visual acuity is often expressed as a *Snellen fraction*, which is the ratio of the distance at which a person can discern two small objects as separate—such as the strokes of a Snellen optotype letter—to the distance at which the separation of the two objects subtends an angle of one minute of arc at the eye. This angle represents the minimum angle

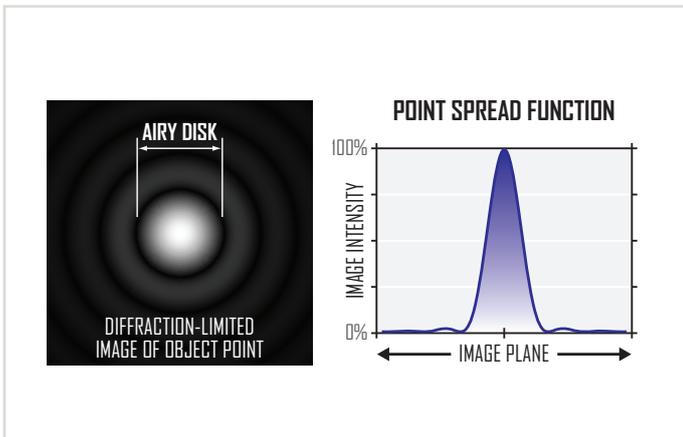


Figure 5: Diffraction of light at a circular aperture from a single object point produces an Airy pattern (shown here enlarged) with a central disc of maximum image intensity surrounded by rings of lower intensity

of resolution of an eye with 'normal' visual acuity. Because the observer usually attempts to identify progressively smaller optotypes at a fixed testing distance, most commonly at 6 metres, this testing distance represents the numerator of the Snellen fraction.

It is also possible to measure the image quality of an optical system such as the eye objectively once the wavefront aberrations have been determined⁴. There are three particularly common objective measures of image quality:

- Root-mean-square error (or RMS)
- Strehl ratio of the point spread function (or PSF)
- Modulation transfer function (or MTF)

The *root-mean-square error* indicates the variance of the aberrated wavefront produced by an optical system from the ideal wavefront over some reference plane. The RMS error is equivalent to the standard deviation of the wavefront error measurements over a regular grid of points. The RMS error of an aberrated wavefront is also easily calculated from the coefficients of the Zernike aberration modes. The contribution of one or more aberration modes to the total RMS error is given by the vector magnitude of their corresponding aberration coefficients:

$$RMS = \sqrt{\sum (C_n^m)^2}$$

where each C_n^m represents the coefficient of a particular Zernike aberration mode. The RMS error of the wavefront up to a given radial order can be determined from the magnitudes of the Zernike coefficients in each of the radial orders up to and including the specified radial order. The *point spread function* indicates

the distribution of image intensity from a single object point across the intended image plane of an optical system. Optical aberrations and diffraction degrade the image of an object point, resulting in a smeared or diffuse point spread function (Figure 6). The total image of a finite object represents the convolution of the point spread function of the optical system for each point on the object, so that each point on the image reflects the aberrated point spread of the corresponding point on the original object.

The *Strehl ratio* indicates the ratio of the peak intensity of the aberrated point spread function to the peak intensity of a diffraction-limited point spread function. The Strehl ratio ranges from 0 to 100%, with a value of 100% indicating a diffraction-limited optical system free from aberrations. Optical aberrations cause a diffusion of the image of an object point, resulting in a less compact point spread function with a lower peak and, consequently, a lower Strehl ratio compared to a diffraction-limited system.

The *modulation transfer function* indicates the capacity of an optical system to reproduce the contrast modulation of a repeating sine wave test pattern as the *spatial frequency* of the pattern—or the number of cycles per unit of distance—increases. *Modulation* refers to the contrast of a test pattern, which is the ratio of the difference between the maximum and minimum luminance levels of the pattern to the average luminance level. Higher spatial frequencies are associated with finer detail. Aberrations prevent an optical system from maintaining high image contrast as the spatial frequency of the object

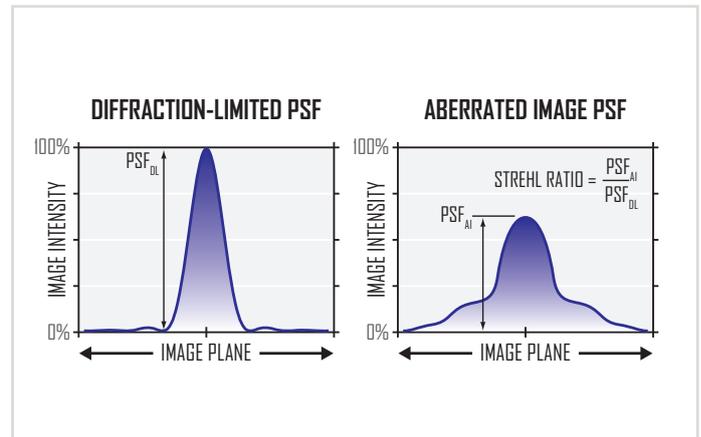


Figure 6: Graphs of the point spread functions of a diffraction-limited optical system and an optical system with significant optical aberrations show the distribution of image intensity

increases. Consequently, the MTF function typically decreases as the spatial frequency increases (Figure 7). The *high frequency cut-off* represents the maximum spatial frequency that can be resolved by the optical system.

Wavefront aberrations of the eye

In vision science, the radial orders of the Zernike polynomial series are routinely categorised as either 'low-order aberrations' or 'high-order aberrations.' *Low-order aberrations* are Zernike modes of the 'second order' or lower ($n \leq 2$). High-order aberrations are Zernike modes of the 'third order' or higher ($n \geq 3$):

- Low-order aberrations include defocus (Z_2^0) and oblique and with-the-rule/against-the-rule astigmatism (Z_2^{-2} and Z_2^2), which are associated with the sphere power and cylinder power of the eye or optical lens, respectively.
- High-order aberrations include vertical and horizontal coma (Z_3^{-1} and Z_3^1), oblique and with-the-rule/against-the-rule trefoil (Z_3^{-3} and Z_3^3), spherical aberration (Z_4^0), and so on.
- While the first-order aberrations of vertical and horizontal prism (Z_1^{-1} and Z_1^1) are also technically low-order aberrations, these Zernike modes as well as the zeroth-order piston mode (Z_0^0) are usually ignored in measurements of image focus quality.

Although Zernike radial orders continue indefinitely, the wavefront aberrations in normal human eyes are usually described adequately by the first six or seven Zernike orders. Low-order aberrations characterise the gross deviation of an aberrated wavefront from the ideal shape required to produce a point focus at the desired location. These aberrations are usually the most detrimental to the

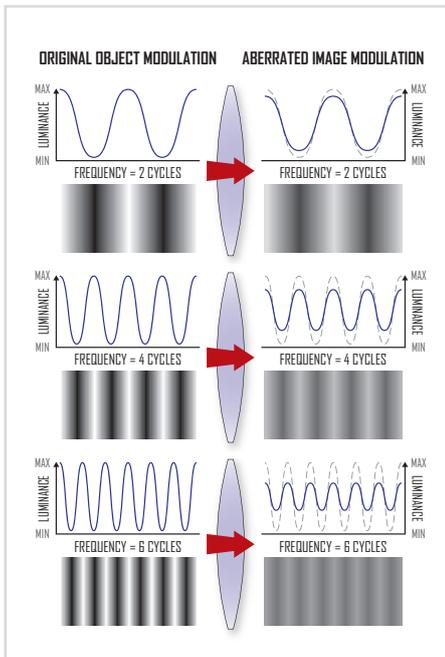


Figure 7: The modulation (or contrast) reproduced by an optical system typically decreases as the spatial frequency of the original test pattern increases due to wavefront aberrations and diffraction

quality of vision for normal eyes. Low-order aberrations are traditionally corrected with prescription spectacle lenses or contact lenses.

High-order aberrations characterise the more subtle deviations of an aberrated wavefront from the ideal shape. In most eyes, high-order aberrations are generally small compared to the low-order aberrations. Generally, these aberrations have less impact on vision quality in normal eyes, although eyes with certain ocular conditions, such as keratoconus, may exhibit significant high-order aberrations. This can result in 'irregular astigmatism' and similar anomalies of ocular refraction. Otherwise, high-order aberrations are usually not visually meaningful until the lower-order aberrations of defocus and astigmatism have been substantially corrected.

Population studies have shown that low-order aberrations typically account for over 90% of the total wavefront error; roughly 80% is due to defocus, alone. These studies have also shown that the RMS wavefront error for the high-order Zernike aberration modes is approximately 0.30 to 0.35 microns on average for a 6mm pupil size, which is equivalent to 0.25 to 0.30 D of second-order Zernike defocus^{5,6}. High-order aberrations are often smaller than the residual defocus and astigmatism remaining after the eye is corrected to

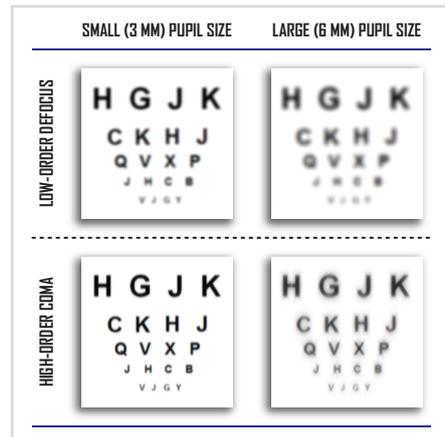


Figure 8: Low-order aberrations degrade image quality significantly, even at smaller pupil sizes, whereas high-order aberrations more detrimental at larger pupil sizes

the nearest one-quarter diopter (0.25 D). High-order aberrations generally decline with radial order and vary significantly from person to person. Moreover, high-order aberrations can fluctuate over time or with variations in accommodation.

Because of the increasing pupil dependence of the aberration modes in the higher radial orders, high-order aberrations become more detrimental to vision quality at low-luminance levels when the pupil size is large (Figure 8). High-order aberrations can reduce image quality by further reducing image contrast and by causing 'halos' and similar effects, particularly around bright lights at night. High-order aberrations can also exacerbate night myopia. Further, because maximum vision quality is essential while operating a motor vehicle in order to ensure adequate reaction time, especially at night, excess high-order aberrations can significantly influence visual performance and even safety.

Refractionists are generally familiar with the effects of low-order wavefront aberrations on vision quality. The second-order Zernike defocus and astigmatism aberrations caused by the uncorrected refractive errors of the eye result in blurred vision and reduced vision acuity, which varies with the magnitude of the refractive error. Only the second-order Zernike aberration modes have coefficients that relate directly to common dioptric powers. It is more difficult to interpret the effects of higher-order aberration modes on vision. Assuming that Zernike aberration modes with equal RMS wavefront errors degrade vision quality equally, however, it becomes possible to relate any

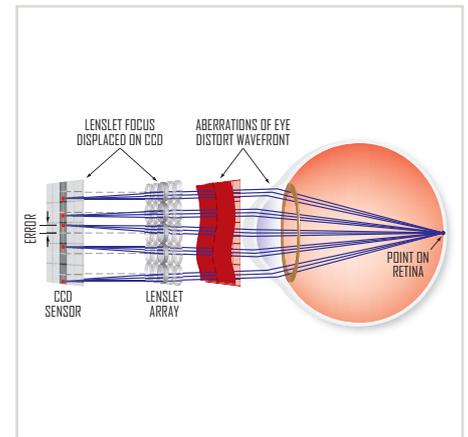


Figure 9: Many commercial aberrometers use a wavefront sensor that is based on the Shack-Hartmann principle, which measures the deflections caused by the distorted wavefront through an array of small lenslets

Zernike aberration mode to the second-order defocus mode. This allows one to express any aberration mode as a 'spherical equivalent' SE in dioptres using the following equation:

$$SE = \frac{-4\sqrt{3}}{\rho^2} C_n^m$$

where C_n^m is the aberration coefficient of the Zernike mode of interest in microns and ρ is the radius of the pupil at which the coefficient C_n^m was determined in millimetres.

The effects of the various Zernike modes on vision quality differ; therefore, the results of this equation should be interpreted with caution. Zernike aberration modes with larger meridional frequencies, which are located farther from the centre of the Zernike pyramid, often have less impact on vision quality than modes with smaller frequencies. Additionally, Zernike modes with the same meridional frequency in different radial orders can interact with each other to improve or degrade vision quality⁷.

Using spherical and cylindrical lenses, a refractionist determines an approximate correction for the second-order aberrations of the eye during the ocular refraction, including any defocus and astigmatism. This refraction is influenced, however, by the high-order aberrations of the eye. Objective refractions based on wavefront measurements should take into account the complex interaction between the high- and low-order aberrations that ultimately leads to the subjective judgment of best focus. In order to measure the high-order

aberrations of the eye, a special device utilising a wavefront sensor is required, which is commonly referred to as an *aberrometer*. Just as a corneal topographer provides more information about the shape of the cornea than a conventional keratometer, an aberrometer provides more information about the optics of the eye than a conventional autorefractor.

Many aberrometers rely on the Shack-Hartmann principle. A point source of light from the aberrometer—representing a distant object—is projected onto the retina. The image

of this point source then serves as the object point for the device. Light from this retinal object point passes through an array of small *lenslets* after leaving the eye. These lenslets sample the optics of the eye over the entire pupil. Each lenslet then brings light to a focus on a CCD sensor. Ideally, light from the retina should produce a plane (flat) wavefront after passing back through the optics of the eye when accommodation is relaxed. Any differences between the ideal plane wavefront and the actual wavefront exiting the eye will cause the light passing through a given lenslet to deviate. The deviation of each focus is

measured and used to model the wavefront errors of the eye (**Figure 9**).

Key points

- Wavefront aberrations represent one of several possible ways to characterise the focusing errors of an optical system.
- The Zernike polynomial series serves as a particularly convenient representation of wavefront aberrations with several useful properties.
- Low-order wavefront aberrations are associated with the traditional sphere and cylinder powers of lenses and are typically the most detrimental to vision quality.
- High-order wavefront aberrations are more detrimental to vision quality at larger pupil sizes or when the lower order aberrations have been eliminated.

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Multiple choice questions (MCQs):

Wavefront aberrations and spectacle lenses: part one

1. Which statement concerning wavefront errors is not true?

- a. The wavefront error is equal to the distance of the refracted ray from the intended focal point
- b. Wavefront error measurements are usually taken across the aperture of an optical system
- c. Wavefront error measurements can be used to predict image quality
- d. The error is the difference in optical path length between the actual aberrated wavefront and the ideal reference wavefront

2. Which relationship is not a common objective measure of image quality?

- a. Modulation transfer function
- b. Visual acuity
- c. Root-mean-square error
- d. Strehl ratio

3. Which Zernike aberration order does a refractionist determine during the ocular refraction part of an eye examination?

- a. Higher order
- b. Lower order
- c. First order
- d. Second order

4. Which objective measure of image quality indicates the variance of the

aberrated wavefront produced by an optical system from the ideal wavefront over some reference plane?

- a. Root-mean-square error
- b. Point spread function
- c. Strehl ratio
- d. Modulation transfer function

5. Which instrument is likely to give the most information about the optics of the eye?

- a. Keratometer
- b. Aberrometer
- c. Autorefractor
- d. Focimeter

6. Which statement about high-order aberrations is not true?

- a. In most eyes high-order aberrations are generally large compared to the low-order aberrations
- b. Excess high-order aberrations can significantly influence visual performance and even safety when driving at night
- c. High-order aberrations include vertical and horizontal coma and spherical aberration
- d. High-order aberrations generally decline with radial order and vary significantly from person to person

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Wavefront aberrations and spectacle lenses

part two

Darryl Meister ABOM, explains the applications of spectacle lenses for the correction of wavefront aberrations in part two of this two-part series

Competences covered:
Target group:

Optical appliances
Dispensing opticians, optometrists

The first installment of this two-part series reviewed the fundamental optical and mathematical principles associated with wavefront aberrations and image quality, with an emphasis on the Zernike polynomial series. The second part now examines the application of wavefront technology to the eye and corrective spectacle lenses. Several spectacle lens manufacturers are now marketing lens designs that minimise the effects of 'high-order' wavefront aberrations. These spectacle lenses generally fall into one of two categories that offer distinctly different potential visual benefits:

1. Spectacle lenses that are claimed to reduce the high-order aberrations of the *spectacle lens*, most commonly in progressive lenses, and
2. Spectacle lenses that are claimed to reduce the effects of high-order ocular aberrations of the *wearer's eye*.

Wavefront aberrations of spectacle lenses

The specified 'power' of an ophthalmic lens is actually based upon a mathematical approximation that is generally only accurate within the *paraxial region* of the lens, or the region of the lens within the immediate vicinity of the optical axis. Calculations of lens power for fabrication purposes are typically based upon this approximation. For instance, the focal power along the optical axis of a 'thin' lens is given by the *Lensmaker's equation*:

$$F = \frac{n-1}{r_1} + \frac{1-n}{r_2}$$

where r_1 is the radius of the front surface in metres, r_2 is the radius of the back surface, and n is the refractive index of the lens material. This relatively simple equation is

derived from a 'small angle' approximation of Snell's law of refraction for small angles of incidence. For relatively small angles, the sine function of the angle is nearly equal to the angle, itself, in radians, so that $\sin i \approx i$ when i is small. This small-angle approximation quickly loses accuracy, however, for object points located at significant distances from the optical axis of the lens, resulting in both low-order and high-order wavefront aberrations. Consequently, the Lensmaker's equation does not adequately describe the refraction of light at significant viewing angles or at significant distances from the optical centre of the lens.

Many eye care professionals are familiar with the traditional optical aberrations that can degrade vision quality through conventional spectacle lenses, which were first



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described in detail by Ludwig von Seidel for rotationally symmetrical optical systems (Figure 1). The aberrated wavefront produced by the Seidel aberrations of an optical system for a given object point or viewing angle can also be broken down or decomposed into a series of Zernike aberration modes. There are five primary Seidel optical aberrations:

1. Seidel curvature of the field occurs when a bundle of light rays refracted through the periphery of a lens is brought to a point focus outside of the intended image plane; this aberration is primarily characterised by the Zernike defocus mode (Z_2^0).
2. Seidel radial astigmatism occurs when a bundle of light rays refracted obliquely through a lens produces an astigmatic focus instead of a single point focus; this aberration is primarily characterised by the Zernike astigmatism modes (Z_2^{-2} and Z_2^2), although Zernike defocus may also be introduced.
3. Seidel spherical aberration occurs when the outer rays in a bundle of light rays are refracted more or less than the inner, paraxial rays near the optical axis; this aberration is primarily characterised by the Zernike spherical aberration mode (Z_4^0).
4. Seidel coma occurs when the outer rays of in a bundle of light rays refracted obliquely through a lens are refracted more than the inner rays; this aberration is primarily characterised by the Zernike coma modes (Z_3^{-1} and Z_3^1).
5. Seidel distortion occurs when the magnification of images of extended objects increases or decreases away from the optical axis of a lens; this aberration is primarily characterised by the Zernike prism modes (Z_3^{-1} and Z_3^1), although distortion will be ignored in this context because it does not influence image clarity.

The Seidel aberration function has field-dependent terms that vary with the angle of view, typically increasing as the angle of view increases. Zernike aberration polynomials, on the other hand, are calculated along a single angle of view. Consequently, in order to characterise the wavefront aberrations of a lens or optical system over an extended field of view using the Zernike polynomial series, Zernike aberration modes must be calculated at multiple angles of view to represent

the rotation of the line of sight behind the lens.

The low-order wavefront aberrations associated with curvature of the field and radial astigmatism are typically the most detrimental to vision quality in conventional single vision and bifocal lenses. These aberrations are generally reduced or eliminated over a sufficiently wide field of view through either judicious base (front) curve selection or the use of an aspheric lens design. When a spectacle lens conforms to proper optical design principles, low-order wavefront aberrations are negligible.

The position of the fitted spectacle lens may also introduce a form of radial astigmatism, resulting in unwanted prescription changes that degrade vision quality. An increase in sphere power and induced cylinder power occur when a spectacle lens is tilted, producing a wavefront aberration that is characterised by the Zernike defocus and astigmatism modes. These power errors vary as a function of the power of the lens and the amount of tilt. With stronger prescriptions, the low-order wavefront aberrations produced by changes in the position of wear of the spectacle lens can be significantly greater in magnitude than the uncorrected high-order aberrations of either the eye or the lens.

For either pantoscopic tilt or face-form wrap of a thin spherical lens of power F , the coefficients for the Zernike defocus and with-the-rule astigmatism modes (C_2^0 and C_2^2) are given by:

$$F_H = F \left(1 + \frac{\sin^2 \theta}{2n} \right)$$

$$F_V = \frac{F_H}{\cos^2 \theta}$$

$$C_2^0 = \frac{F_V + F_H}{-8\sqrt{3}} \rho^2$$

$$C_2^2 = \frac{F_V - F_H}{4\sqrt{6}} \rho^2$$

where F_H is the power through the horizontal meridian of the lens, F_V is the power through the vertical meridian, n is the refractive index of the material, ρ is the radius of the pupil in millimetres, and θ is the angle of lens tilt. For face-form wrap, the sign of C_2^2 should be

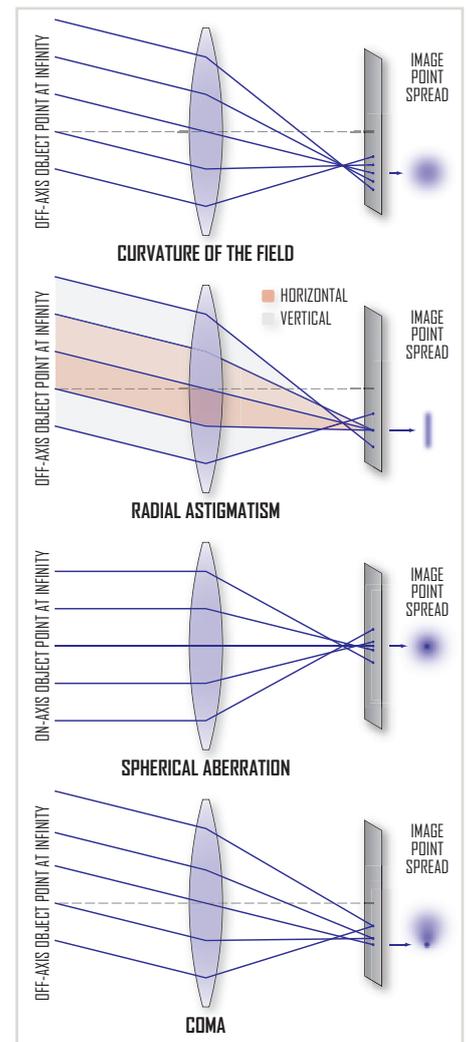


Figure 1: The primary Seidel aberrations that affect image clarity include curvature of the field, radial astigmatism, spherical aberration, and coma

changed from positive to negative or vice versa. The Zernike oblique astigmatism mode (C_2^{-2}) is zero in this simplified case.

Spectacle lenses may also introduce high-order wavefront aberrations, such as spherical aberration and coma, particularly in stronger prescription powers. Spherical aberration is due to an effective increase in refractive power away from the optical axis of a lens, causing rays of light in the periphery to focus more closely to the lens than light rays near the optical axis. Coma is due to a variation in refractive power that affects extended object points located away from the optical axis of the lens. Fortunately, the relatively small pupil aperture of the eye 'stops down', or limits the area of the lens used for focusing light from any given object point across the field of view, which

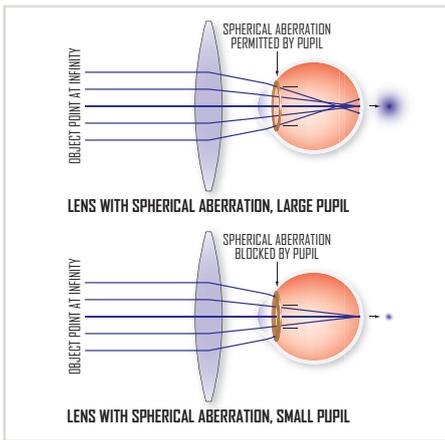


Figure 2: The small pupil aperture of the eye effectively limits the amount of spherical aberration and coma introduced by spectacle lenses

reduces the effects of these two aberrations considerably (Figure 2).

Properly designed single vision and bifocal lenses typically produce only negligible amounts of low-order and high-order aberrations in most prescription powers. The optical limitations of progressive lenses, on the other hand, introduce meaningful levels of both low-order and higher-order aberrations. In any case, minimising the wavefront aberrations produced by a spectacle lens will not provide the wearer with better than his or her best corrected visual acuity.

Wavefront aberrations of progressive lenses

Progressive lenses produce significant second-order wavefront aberrations, particularly in the lateral 'blending' regions of the lens. Providing a progressive change in addition power requires a surface that varies smoothly in curvature. The mathematical constraints of producing a smooth change in curvature along the progressive corridor, however, result in surface astigmatism, or a difference in curvature at any given point, away from the progressive corridor of the lens. Minkwitz showed mathematically that, in the vicinity of the progressive corridor at least, the unwanted surface astigmatism lateral to the progressive corridor increases twice as rapidly as the change in addition power along the corridor.

The unwanted cylinder power produced by the refraction of light through the surface astigmatism of a progressive lens introduces significant

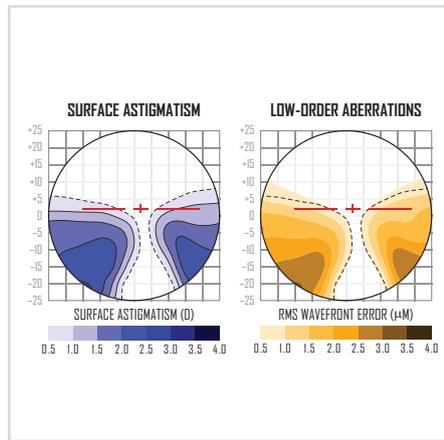


Figure 3: The low-order wavefront aberrations of a progressive lens are due primarily to unwanted surface astigmatism in the 'blending' regions of the lens, as demonstrated by contour plots of surface astigmatism and RMS wavefront errors for a 6mm pupil at each point over the lens

quantities of Zernike oblique and with-the-rule astigmatism modes (Z_2^{-2} and Z_2^2), which contribute significantly to the overall shape of the aberrated wavefront. The low-order wavefront aberrations of a progressive lens are due primarily to this unwanted astigmatism (Figure 3). The distribution of addition power over the lens surface can also result in blur from insufficient or excess plus power for a given viewing distance when the object of regard is either too close or too far away. The contribution of this power error to the aberrated wavefront is characterised by the Zernike defocus mode (Z_2^0).

Furthermore, the smooth change in addition power and surface astigmatism over the progressive lens introduces non-negligible levels of high-order wavefront aberrations that are characterised by the Zernike wavefront aberration modes associated with variations in curvature, particularly the modes of the third radial order, coma and trefoil*. In fact, it can be demonstrated mathematically that the refracting action of a simple progressive lens surface, with circular cross-sections and a linear progression of addition power, can be reproduced by combining an equal quantity of vertical coma (Z_3^{-1}) and oblique trefoil

* Mathematically, curvature is associated with the second derivatives of a surface, whereas a variation in curvature is associated with the third derivatives of the surface; Zernike third-order aberrations modes exist when a refracted wavefront has non-zero third derivatives.

(Z_3^{-3}). The coefficients C_3^{-1} and C_3^{-3} of these two Zernike aberration modes depend upon the rate of change in addition power along the progressive corridor¹:

$$C_3^{-1} = \frac{\delta A}{24\sqrt{2}} \rho^3 = \frac{1}{24\sqrt{2}} \left(\frac{A}{h}\right) \rho^3$$

$$C_3^{-3} = \frac{\delta A}{24\sqrt{2}} \rho^3 = \frac{1}{24\sqrt{2}} \left(\frac{A}{h}\right) \rho^3$$

where ρ is the radius of the pupil in millimetres and δA is the rate of change in addition power in dioptres per millimetre, which is the equal to the ratio of the addition power A to the corridor length h , or $\delta A = A/h$.

The progression of addition power essentially acts as a coma-like wavefront aberration along the progressive corridor, while the astigmatism-free nature of the corridor is achieved by a trefoil-like wavefront aberration over the same region. Further, these aberrations are proportional to the rate of change in addition power (δA) along the progressive corridor of the surface. Additionally, these equations for the third-order Zernike coefficients demonstrate the pupil size dependence (ρ^3) of the third-order wavefront aberrations produced by progressive lenses, which vary as the third power of the pupil size.

Traditional coma is due to an asymmetric variation in refractive power and magnification across the lens for object points away from the optical axis. The change in addition power across a progressive lens surface produces a very similar effect. As the line of sight passes down the progressive corridor of the lens, the power at the upper margin of the pupil differs from the power at the lower margin by an amount roughly equal to the product of the pupil diameter and the rate of change in addition power at that particular location. In fact, coma is directly proportional to the rate of change in mean addition power at any point across the lens surface (Figure 4).

Although the Zernike coma and trefoil aberration modes remain constant over the progressive region of the

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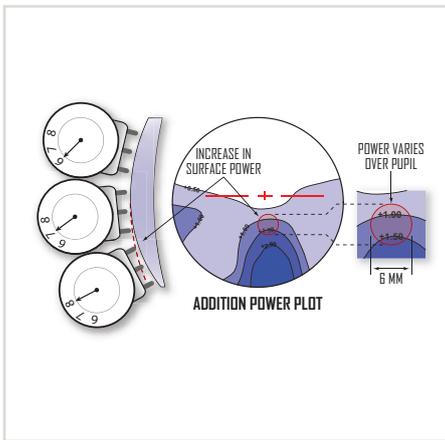


Figure 4: The progression of addition power across a progressive lens surface causes the power to vary over the finite diameter of the wearer's pupil, introducing a coma-like wavefront aberration

simple surface discussed earlier, modern progressive lenses employ non-circular cross-sections and addition power that varies non-linearly along the corridor. Nevertheless, the high-order Zernike aberration modes in these lenses will vary with the rate of change in surface power at any point. Coma and trefoil will be highest in regions wherein the addition power and surface astigmatism are changing most rapidly (**Figure 5**). Moreover, since high-order wavefront aberrations depend upon the rate of change in surface power, these aberrations will be more significant in progressive lenses with shorter corridor lengths or higher addition powers.

Progressive lens designers have begun paying closer attention to high-order wavefront aberrations, and in some cases even developing progressive lens designs with reduced high-order aberrations². Unfortunately, you cannot *eliminate* the high-order aberrations produced by a progressive lens surface, just as you cannot eliminate unwanted surface astigmatism. In fact, for modern, well-designed progressive lens designs at least, the average levels of high-order aberrations calculated globally over each lens surface are often similar in magnitude (**Figure 6**)³. Nevertheless, you can judiciously *manage* both the low-order and high-order aberrations of a progressive lens.

Just as there are two general approaches to the management of low-order astigmatism and defocus, by either distributing the 'blending' region over a larger area of the

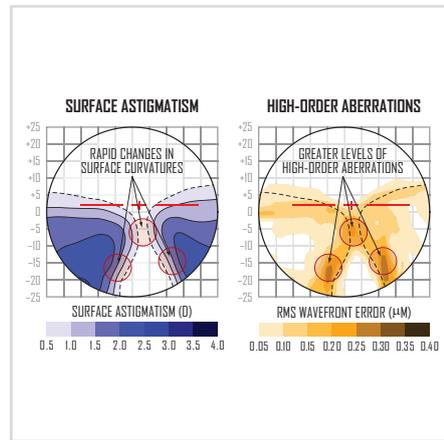


Figure 5: High-order aberrations are greatest over regions of the lens in which the addition power and astigmatism are changing rapidly

surface to 'soften' the design or confining the region to a smaller area to 'harden' the design, there are also two intimately related approaches to the management of high-order aberrations. A 'soft' lens design with gradual power changes will typically yield relatively low levels of high-order aberrations over the entire lens, whereas a 'hard' lens design with rapid power changes will yield lower levels of high-order aberrations in the central distance and near viewing zones, while creating greater levels at the viewing zone boundaries and within the progressive corridor. In general, minimising high-order aberrations in any particular region will be at the expense of inducing greater levels of high-order aberrations elsewhere⁴.

Although high-order aberrations may result in a reduction in image quality and a loss of contrast, low-order lens aberrations generally account for the greatest impact on vision quality with progressive lenses. The maximum RMS wavefront error for the low-order aberrations is up to ten times greater than the maximum error for the high-order aberrations (**Figure 7**). In particular, unwanted astigmatism dominates much of the lens. Further, in contrast to the low-order aberrations, clinical research has demonstrated that the high-order aberrations of progressive lenses are seldom any greater in magnitude than the natural high-order aberrations of a typical wearer's eyes⁵. Consequently, for the correction of presbyopia with progressive lenses, which suffer from significant low-order aberrations, the

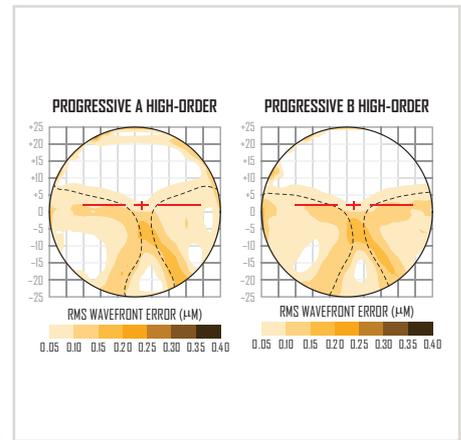


Figure 6: Well-designed progressive lenses often exhibit similar levels of high-order aberrations as demonstrated by plots of RMS wavefront errors over each lens surface

distribution of power and unwanted astigmatism over the lens design will undoubtedly serve as a greater indicator of wearer satisfaction.

Research has also demonstrated that the impact of high-order lens aberrations on visual acuity in the progressive corridor, where these aberrations are often highest, is negligible. The caustic focus produced in the presence of small amounts of high-order lens aberrations may possibly improve the wearer's depth of focus and tolerance to the blur caused by the second-order aberrations of the lens. In fact, aberration coupling between the high-order aberrations of the progressive lens and the high-order aberrations of the eye can sometimes yield better visual acuity than obtained with the naked eye⁶. Nevertheless, the high-order aberrations produced by a progressive lens will have at least some impact on the wearer's vision, and therefore represent a meaningful quantity to evaluate during the optical design process.

Correcting the wavefront aberrations of the eye

Spectacle and contact lenses are generally prescribed to correct the low-order aberrations of the eye, corresponding to the Zernike defocus and astigmatism modes. If the low-order aberrations of eye have been corrected with lenses, vision quality becomes limited by any residual high-order aberrations, such as spherical aberration and coma, particularly at larger pupil sizes. Visual acuity for

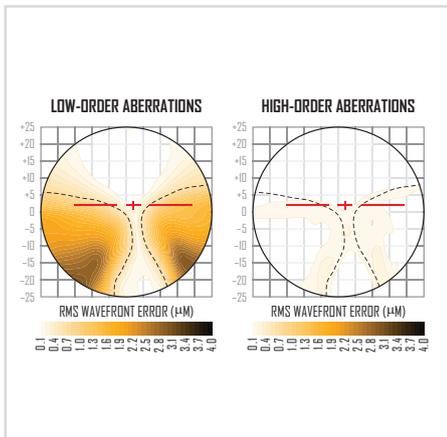


Figure 7: Low-order aberrations due to unwanted surface astigmatism are significantly greater in magnitude than high-order aberrations over most of the progressive lens surface

'normal' individuals, without significant ocular pathology, ranges from 6/6 to 6/5 under typical testing conditions when the low-order aberrations have been corrected with lenses. If both the low-order and high-order aberrations of the eye are eliminated, however, *super vision* may be obtained with improved contrast sensitivity and supernormal visual acuity that is noticeably better than 6/6 (Figure 8).

Once the low-order and high-order aberrations of the eye have been completely eliminated, diffraction becomes the limiting factor in image resolution at small pupil sizes. *Rayleigh's criterion* states that, in order to distinguish two objects points as separate, sufficient distance must separate the central Airy patterns of the two image points. At larger pupil sizes, the resolution of the human eye becomes limited by the anatomical density of the retinal photoreceptors, or the number of cones over a given region of the retina, which is a 'sampling frequency' limitation known as the *Nyquist limit*. Additionally, the chromatic aberration of the eye for different wavelengths of light serves as another optical limitation. Therefore, due to the optical and physiological limitations of the human eye, even a perfectly corrected eye free from optical aberrations can only achieve 6/3 to 6/4 visual acuity.

Nevertheless, there exists potential for an improved visual outcome. 'Wavefront-guided' corneal ablation is quickly becoming the new standard of care in refractive surgery. Wavefront-guided ablation promises

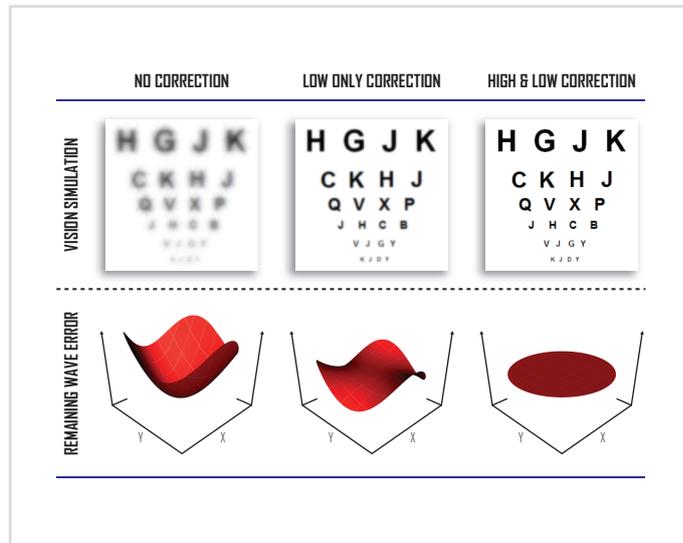


Figure 8: Once the low-order aberrations of the eye have been corrected, which are typically more detrimental, visual performance becomes limited by high-order aberrations

to improve visual performance, at least compared to post-operative results obtained using traditional methods, by modifying the ablation profile based upon the high-order aberrations of the eye. Because of variations in wound healing and other factors influencing surgical outcomes, however, it is difficult to correct completely the subtle high-order aberrations of the eye through surgery. Often, patients do not experience a notable improvement in visual acuity compared to their best spectacle correction prior to refractive surgery⁷.

It is also possible to incorporate a correction for certain high-order aberrations into soft contact lens designs, since it is possible to cause these lenses to remain relatively fixed with respect to the optics of the eye by minimising rotational and translational movements about the cornea. Unfortunately, spectacle lenses cannot eliminate the high-order aberrations of the eye without introducing additional, lower-order aberrations as the eye rotates from the centre of the lens. For instance, correcting second-order aberrations results in induced first-order prism as the eye moves from the centre of the correction (that is, *Prentice's rule*), while correcting third-order aberrations results in induced second-order astigmatism and defocus errors.*

* This effect can be appreciated by adding a horizontal or vertical offset to the terms of a Zernike basis function, and then expanding the new binomials, so that a term such as $2x^2$ in a Zernike polynomial becomes $2(x + \Delta x)^2 = 2x^2 + 4x\Delta x + 2\Delta x^2$ in the presence of a horizontal offset (Δx), now with lower-order $4x\Delta x$ and $2\Delta x^2$ terms.

In fact, just a few millimetres of movement of the line of sight from the centre of an ideal wavefront correction will introduce new, lower-order wavefront errors that are actually greater in magnitude than the higher-order aberrations initially eliminated, and these errors will progressively worsen with increasing movement⁸. Since the human eye remains in a constant state of movement, correcting the high-order aberrations of the eye with a spectacle lens actually results in poorer vision quality over most of the wearer's field of view. Thus, the sensitivity of these aberrations to normal gaze changes places drastic limits on the visual benefits of correcting the high-order aberrations of the eye with a spectacle lens.

Although there are significant optical limitations associated with eliminating the high-order aberrations of the eye with a spectacle lens, it is possible to determine better 'low-order' spectacle corrections by considering the influence of high-order aberrations on vision. The optimum prescription is influenced by not only the low-order sphere and cylinder refractive errors, but also by the higher-order aberrations of the eye at a given pupil size.

Determining the endpoint of refraction by taking into account the effects of high-order aberrations on blur may result in more accurate low-order spectacle refractions that deliver optimum vision over a broader range of luminance levels or viewing

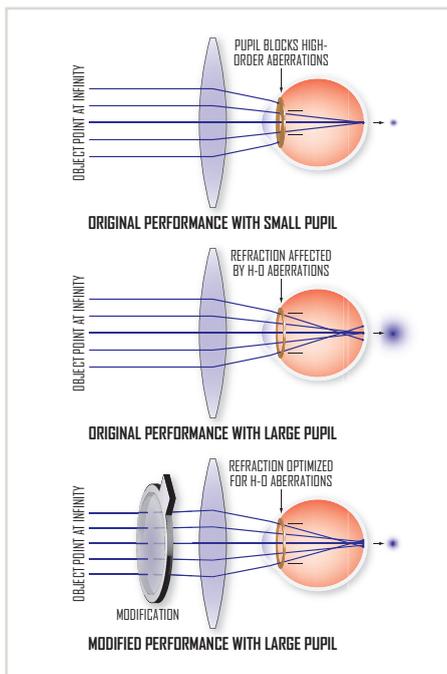


Figure 9: Wavefront-guided prescriptions can fine-tune the low-order spectacle refraction to ensure maximum vision quality across a range of pupil sizes

conditions. Using wavefront data captured by an aberrometer, a *wavefront-guided* or *wavefront-optimised* spectacle refraction can be determined objectively by calculating the prescription powers that maximise some predefined measure of retinal vision quality⁹. Conventional autorefractors have not replaced subjective refraction as the best method to determine the final low-order spectacle prescription powers. Furthermore, the accuracy of the forced-choice method typically utilised during subjective refraction to determine the final spectacle correction for an eyeglass wearer suffers from the inherent variability of subjective responses^{10,11}.

The patient may use different perceptual criteria—such as sharpness, contrast, or legibility—when choosing the 'best focus', which may correspond to differing lens powers. The depth of focus of the eye may make it difficult for the patient to discriminate reliably between small changes in vision quality when presented with multiple lenses for comparison. Although the effect is ameliorated somewhat by the directional sensitivity of the retina, known as the *Stiles Crawford* effect, the spherical equivalent of the refraction may vary with pupil size in

the presence of significant high-order aberrations such as spherical aberration. The Jackson cross-cylinder technique may fail to converge to the ideal cylinder power correction in the presence of high-order aberrations or the inability of the patient to determine the relative legibility of Snellen chart letters that have been distorted in shape or caused to 'ghost' by cylinder power.

In addition to the potential variability of subjective refraction, the use of lenses in one-quarter dioptre (0.25D) increments during the refraction procedure places a limitation on the measurement precision of the final prescription powers, resulting in rounding errors of up to $\pm 0.125D$. Traditional lens surfacing relies on hard lap tooling to produce the prescription surface, which is typically limited in precision to $\pm 0.0625D$. The propagation of rounding errors from refraction and surfacing can contribute up to 0.2D of unwanted power error.

Because aberrometers capture extensive data regarding the wavefront aberrations of the eye over the entire pupil, it becomes possible to modify the traditional low-order spectacle refraction by taking into account the effects of high-order aberrations on retinal image quality, to the nearest one-hundredth dioptre (0.01D). Software employing optimisation algorithms can calculate the spectacle refraction that delivers the best retinal image quality at a given pupil size or range of pupil sizes without the limitations imposed by conventional autorefractors or even subjective refraction (**Figure 9**).

Consequently, when combined with sophisticated computer programs that maximise vision quality based upon the wavefront aberration data of the eyes, aberrometry can potentially deliver more accurate and reliable vision corrections compared to traditional subjective refraction¹². It is even possible to reconcile the wavefront-guided refraction against the manifest subjective refraction in order to preserve any deliberate changes to the ocular refraction meant to balance the stimulus to accommodation or otherwise ensure

comfortable binocular vision.

Furthermore, with the advent of free-form surfacing technology, lens surfacing no longer needs to be constrained by the rounding errors of hard lap tooling. Free-form surfacing technology enables laboratories to fabricate lenses that precisely replicate prescription powers in one-hundredth dioptre (0.01 D) increments. When a wavefront-guided spectacle prescription is fabricated to more precise optical tolerances, the result is a truly optimum low-order vision correction that provides improved contrast sensitivity and visual acuity under a wider range of luminance levels or viewing conditions¹³. Someday, this technology may very well supplant the current model of eyewear delivery by establishing a new standard of care for prescribing and fabricating spectacle corrections.

Key points

- Spectacle lenses cannot correct the high-order aberrations of the eye without introducing even greater aberrations away from the centre of the lens.
- Properly designed single vision and bifocal lenses generally suffer from only negligible low-order and high-order aberrations.
- Changing addition power and unwanted astigmatism over progressive lenses introduces significant low-order and high-order aberrations.
- Spectacle prescriptions can be enhanced using both low-order and high-order aberration measurement data from an aberrometer to maximise vision quality over a broad range of pupil sizes.

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Next issue: Stephen Freeman describes the history, technology and applications of current photochromic and polarised lenses

Multiple choice questions (MCQs):

Wavefront aberrations and spectacle lenses: part two

1. Which Seidel aberration is primarily characterised by the Zernike defocus mode?

- a. Seidel curvature of the field
- b. Seidel radial coma
- c. Seidel spherical aberration
- d. Seidel distortion

2. Which two of the Seidel aberrations are both effectively limited by the small size of the pupil of the eye?

- a. Radial astigmatism and coma
- b. Spherical aberration and coma
- c. Spherical aberration and distortion
- d. Radial astigmatism and spherical aberration

3. How is it possible to eliminate the high-order aberrations on a progressive lens surface?

- a. By distributing the 'blending' region of the surface

b. By confining the 'blending' region to a smaller area

c. By balancing the high-order aberrations with the low-order aberrations

d. None of the above; it is impossible to eliminate all of the high-order aberrations

4. Which person showed mathematically that, in the vicinity of the progressive corridor, the unwanted surface astigmatism lateral to that corridor increases twice as rapidly as the change in addition along the corridor?

- a. Von Seidel
- b. Minkwitz
- c. Nyquist
- d. Zernike

5. Which statement is most likely to be true regarding the impact of

aberrations upon vision quality with progressive lenses?

a. High-order aberrations have more impact on vision quality than low-order

b. High-order lens aberrations in are noticeably greater than the natural high-order aberrations of the eye

c. High-order aberrations may result in a reduction in image quality and a loss of contrast

d. Low-order aberrations generally have less impact on vision quality with progressive lenses

6. Which aberration will most likely be induced if the pantoscopic tilt or face form angle of a pair of lenses is altered?

- a. Radial astigmatism
- b. Curvature of the field
- c. Distortion
- d. Spherical aberration

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