Predicting subjective judgment of best focus with objective image quality metrics

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Purpose: To determine the impact of higher-order monochromatic aberrations on lower-order subjective sphero-cylindrical refractions. Methods: Computationally-aberrated, monochromatic Sloan letters were presented on a high luminance display that was viewed by an observer through a 2.5mm pupil. Through-focus visual acuity (VA) was determined in the presence of spherical aberration ($Z_4^2$) at three levels (0.10, 0.21 and 0.50D). Analogous through-astigmatism experiments measured visual acuity in the presence of secondary astigmatism ($Z_3^3$) or coma ($Z_5^3$). Measured visual acuity was correlated with 31 different metrics of image quality to determine which metric best predicts performance for degraded retinal images. The defocus and astigmatism levels that optimized each metric were compared with those that produced best visual acuity to determine which metric best predicts subjective refraction. Results: Spherical aberration, coma and secondary astigmatism all reduced VA and increased depth of focus. The levels of defocus and primary astigmatism that produced the best performance varied with levels of spherical aberration and secondary astigmatism, respectively. The presence of coma, however, did not affect cylindrical refraction. Image plane metrics, especially those that take into account the neural contrast sensitivity threshold (e.g. the visual Strehl ratio, VSOTF), are good predictors of visual acuity in both the through-focus and through-astigmatism experiments ($R = -0.822$ for VSOTF). Subjective sphero-cylindrical refractions were accurately predicted by some image-quality metrics (e.g., pupil fraction, VSOTF and standard deviation of PSF light distribution). Conclusion: Subjective judgment of best focus does not minimize RMS wavefront error (Zernike defocus = 0), nor create paraxial focus (Seidel defocus = 0), but makes the retina conjugate to a plane between these two. It is possible to precisely predict subjective sphero-cylindrical refraction for monochromatic light using objective metrics.

Keywords: visual optics, metrics of optical quality, best focus

Introduction

With the introduction of modern aberrometry into the clinical environment, it is now possible to routinely assess the monochromatic aberrations of the human eye (Cheng, Himebaugh, Kollbaum, Thibos, & Bradley, 2003, 2004). This technology is currently being employed as a guide for photoablative lasers attempting to correct higher order aberrations in the optics of the eye (MacRae, Krueger, & Applegate, 2001; Mrochen, Kaemmerer, & Seiler, 2001; Nagy, Palagi-Deak, Kelemen, & Kovacs, 2002; Nagy, Palagi-Deak, Kovacs, Kelemen, & Forster, 2002). It is also tempting to anticipate that such a detailed description of the eye's optics could be employed to generate highly accurate automated sphero-cylindrical refractions (Chen et al., 2003; Guirao & Williams, 2003; Thibos, Bradley, & Applegate, 2003). We examine this possibility in the present manuscript.

Automated sphero-cylindrical refractors have been available since 1970s, but they are currently only employed to provide an approximate estimate of the refractive error and as a substitute for retinoscopy but not an alternative to the subjective refraction (Bullimore, Fusaro, & Adams, 1998; Campbell, Benjamin, & Howland, 1998; Goss & Grosvenor, 1996). Although we generally consider the subjective refraction as the "gold standard" for refraction in that it is the sphero-cylindrical lens that provides best subjective performance, it can be quite variable (Bullimore et al., 1998; Goss & Grosvenor, 1996). Therefore improved automated refractions have the potential to provide accurate and more reliable prescriptions than the current "gold standard". Although high-resolution aberrometry data might seem to provide a possible advance in automated refractions, they reveal a fundamental problem for determining the refractive error. Because the optical system of human eyes is aberrated (Castejon-Mochon, López-Gil, Benito, & Artal, 2002; Porter, Guirao, Cox, & Williams, 2001; Thibos, Hong, Bradley, & Cheng, 2002), a sphero-cylindrical correcting lens cannot generate a truly focused image. Irrespective of the correcting lenses used, some parts of the beam generating the retinal image will always be blurred. Therefore, in this situation, it is not immediately obvious which sphero-cylindrical lens will provide the best image quality.
There are many ways to define image quality, e.g. pupil plane metrics and image plane metrics (Cheng, Thibos, & Bradley, 2003; Thibos, Hong, Bradley, & Applegate, 2004), and the data generated by an aberrometer can be used to calculate a wide variety of such image quality metrics (e.g. wavefront error RMS, PSF widths, volume under the OTF etc.). The question examined in this paper is whether subjective refractions are affected by the presence of higher order aberrations and whether the subjective refractions of aberrated eyes can be accurately predicted by such objective image quality metrics. Thibos et al (Thibos, Hong et al., 2002) showed that carefully refracted subjects still had significant amounts of residual Zernike defocus (Z_2^0), which means that the RMS wavefront error was not minimized by a subjective refraction. Similar results were found by Guirao et al who reported that refraction based on minimum RMS wavefront error made the eye myopic while refraction based on paraxial focus made the eye hyperopic (Guirao & Williams, 2003). In addition, in a previous study (Cheng, Bradley, Thibos, & Ravikumar, 2003) we found that, in the presence of spherical aberration, visual acuity was better with paraxial focus than with the defocus that minimized RMS. Although subjective refractions achieve approximate paraxial focus, a systematic paraxial defocus still exists (Thibos, Hong et al., 2002). Thus, these previous studies all indicate that subjective refractions in aberrated eyes do not minimize RMS, and probably do not achieve paraxial focus, which poses the question of what optical characteristic or image quality property is optimized during a subjective refraction.

The impact of aberrations on vision can be studied with two quite different methodologies. First, aberration levels in the eye can be manipulated directly by interposition of lenses (Bradley, Thomas, Kalaher, & Hoerres, 1991), phase plates (Lopez-Gil, Howland, Howland, Charman, & Applegate, 1998), or deformable mirrors (Artal et al., 2003; Chen et al., 2003; Williams, 2002) into the visual path. Alternately, the displayed stimulus can be computationally aberrated and degraded (Applegate, Ballentine, Gross, Sarver, & Sarver, 2003; Applegate, Marsack, & Ramos, 2003; Applegate, Sarver, & Khemsara, 2002). Chan et al (Chan, Smith, & Jacobs, 1985) characterized these two approaches as the “source” (defocused display) and “observer” (defocusing the eye) methods, and demonstrated their equivalence for spherical defocus. The computational blurring method has flexibility and cost advantages over phase plates, lenses and deformable mirrors. However, in order to simulate aberrated retinal images accurately, all sources of image degradation between the digital image and the retina (e.g., the non-linearity and demodulation of the display and the demodulation from the subject’s optics) must be pre-compensated for in the digital image.

Using computationally aberrated images, we have examined the relationship between image quality determined subjectively (visual acuity) and 31 different objective measures of image quality in an attempt to identify those metrics that correlate with visual performance and could be used for accurate automated refractions.

**Methods**

The experimental setup was designed to examine visual acuity with computationally aberrated images. Using the computational methods of Fourier optics, aberrated images of Sloan letters were computed as the convolution of the object and point-spread function (PSF) of an eye with an assigned wavefront aberration function over a 5mm pupil. This convolution was performed in the frequency domain to facilitate pre-compensation for demodulation caused by the projection system and the eye’s optics. This pre-compensation was achieved by dividing the computed image spectra by the display optical transfer function (OTF) and by the diffraction-limited OTF of the subject’s eye. The computed images were displayed as visual stimuli on a high luminance (3045cd/m^2) gamma-corrected, rear-projection screen viewed through an interference filter (λ = 556nm). The luminance of this monochromatic stimulus viewed by the subject was 264cd/m^2. Subjects viewed the simulated images through a unit magnification relay telescope, which conjugated a 2.5mm artificial pupil centered on the primary line of sight with the subject’s entrance pupil plane. The 2.5mm artificial pupil ensured that the subject’s eye was approximately diffraction-limited (confirmed experimentally) and was computationally convenient. In this way, visual acuity could be evaluated with controlled levels of monochromatic aberrations.

During a clinical subjective refraction, the impact of spherical defocus and astigmatic defocus are observed in the presence of numerous ocular higher order aberrations. Standard nomenclature for Zernike coefficients (Thibos, Applegate, Schwiegerling, & Webb, 2002) are used in this paper. We simulated this experience in the current experiment by modulating the amount of spherical defocus (Z_2^0) in the presence of three possible levels of spherical aberration (Z_4^0) when computing blurred stimuli. Similarly, we examined the impact of astigmatic defocus (Z_3^1±2) in the presence of secondary astigmatism (Z_4^1±2) or coma (Z_3^0). These experiments are, therefore, controlled analogues of the standard subjective refraction in which through-focus or through-astigmatism plots of acuity are obtained.

The aberrations used to degrade the stimuli were combinations of 3 levels of Zernike higher order aberrations (Z_0^0, Z_2^0, Z_4^0, Z_4^2, or Z_4^4) with 7 or 8 of levels of Zernike defocus (Z_2^0) or astigmatism (Z_3^1±2) for a 5mm pupil diameter. The three levels of higher-order aberrations were 0.10D, 0.21D and 0.50D of equivalent defocus, where equivalent defocus (in diopters) is given by the following equation (Thibos, Hong et al., 2002).

\[
M_e = 4\pi\sqrt{3} \frac{\text{RMS}}{\text{pupil area}}
\]
The two smaller levels of higher-order aberrations are equal to the mean and 95th percentile level of spherical aberration found in young adult eyes (Thibos, Hong et al., 2002). The larger level is non-physiological for normal eyes but may occur in surgically altered eyes. The range of Zernike defocus included that value which minimized total RMS wavefront error (zero Zernike defocus) and that value which produced paraxial focus (e.g., $\sqrt{15}$ times the amount of spherical aberration (Thibos, Hong et al., 2002)).

Visual acuity was derived from psychometric functions of percent correct versus letter size. A logarithmic series of eight to ten letter sizes each presented ten times were used to generate each psychometric function. Letter sizes and individual Sloan letters were randomly sequenced. Visual acuity in logMAR units was the letter size that gave a 55% correct performance (interpolated using a Weibull fit to the data) (Cheng, Bradley et al., 2003).

Interpolated visual acuities were plotted as a function of defocus or astigmatism, and these through-focus plots were fitted by the least-squares method with 5th order polynomials. The “subjective” best-focus corresponded, therefore, to the amount of the Zernike defocus or primary astigmatism that maximized visual acuity.

The aberrated wavefronts used to compute the blurred letter images were also used to compute a large set ($n = 31$) of optical quality metrics for every aberration condition used experimentally. Detailed descriptions of these metrics are given in the accompanying paper (Thibos, Hong et al., 2004). A simple clarification of the acronyms is given in Table 2 in the Appendix). These metric values were correlated with logMAR acuity to evaluate their success at predicting visual performance. Since logMAR and metrics are both dependent variables, we used principal component analysis to determine the orthogonal regression line. We also determined the level of defocus or astigmatism that optimized each metric to evaluate the accuracy and precision with which each metric predicted subjective best focus.

**Results**

The through-focus visual acuity data and samples of blurred stimuli are shown in Figure 1. Each panel displays images of a letter (D) degraded by the same levels of higher and lower order aberrations that were used to assess visual acuity. The three rows of letter images in panels A, C and D represent the three levels of 4th order aberration (0.10, 0.21, and 0.50D of equivalent defocus). The two rows of letter images in panel B represent the two levels of 3rd order coma (0.00D and 0.50D) tested. The letter images within each row reflect the different levels of spherical defocus (panel A) or astigmatism (panels B, C and D) used to generate the through-focus plots of visual acuity. Through-focus logMAR acuities are shown within panels A, C & D for the three different levels of 4th order aberrations (triangles = 0.10D, circles = 0.21D and squares = 0.50D) and for two subjects (solid and open symbols). Only one subject and two levels (0.00 and 0.50D) of coma were tested.

The through-focus acuity data in Figure 1A clearly show that the presence of 4th order spherical aberration ($Z_4^{(s)}$) impacts the visual effect of defocus ($Z_0^{(s)}$) in several ways. First, the best achievable visual acuity deteriorates with increasing levels of spherical aberration. Second, confirming Applegate et al. (Applegate, Marsack, & Ramos, 2003), the amount of Zernike spherical aberration influenced the amount of defocus needed to produce the best visual acuity. Third, increasing levels of Zernike spherical aberration significantly decreased the change in logMAR produced by defocus and thus increased the depth of focus. The results in panels C&D show that the presence of secondary astigmatism ($Z_4^{(s^2)}$) had a similar influence on the visual effect of second order astigmatism ($Z_2^{(s^2)}$). The presence of coma also reduced the best achievable visual acuity and increased the depth of focus. It did not, however, change the level of astigmatism necessary to achieve best acuity. When MAR approached its minimum levels (at “best focus”), one subject’s acuity was consistently 0.1 log units better than the other. We assume this reflects a genuine neural difference between these two subjects.

The wavefronts used to generate blurred letters with fourth order aberrations (spherical aberration and secondary astigmatism) were used to calculate a large number ($n = 31$) of optical and image-quality metrics. Metric amplitude was then correlated with logMAR visual acuity observed for these same conditions (all of the data in Figure 1A, C and D). The scattergrams in Figure 2 show 3 examples of optical and image-quality metrics, which were reasonably well correlated with logMAR visual acuity (left panels) and 3 examples that were poorly correlated (right panels). In each case (good correlation and poor correlation), we illustrate examples of wavefront-based, PSF-based and OTF-based metrics. The metric of “pupil fraction” (PFSt, the fraction of pupil area for which the optical quality of the eye is reasonably good, Cheng, Thibos, & Bradley, 2003) was well correlated with acuity ($R = -0.837$), whereas RMS wavefront error (RMSw) was poorly correlated ($R = 0.493$). Also, two PSF metrics produced different correlations: the standard deviation of intensity values in the PSF, normalized to diffraction-limited value (STD, $R = -0.816$) and PSF halfwidth-at-half height (HWHH, $R = 0.365$). Finally, visual Strehl ratio (VSOTF, the contrast-sensitivity-weighted OTF divided by contrast-sensitivity-weighted OTF for diffraction limited optics, Cheng, Himebaugh, Kollbaum, Thibos, & Bradley, 2004) correlated well with logMAR ($R = -0.822$), whereas the metric designed to capture the phase changes in the image, OTF/MTF ratio (VOTF), was poorly correlated with acuity ($R = -0.182$). It is interesting to see that the metric of VOTF successfully divided the data points in to two distinct parts. The data points at the bottom area of Figure 2F represent visual acuity obtained under the aberration conditions that introduced large phase shifts (VOTF < 1), whereas the data points at the top area of Figure 2F represent visual acuity obtained under
aberration conditions that maintained phase (VOTF ≈ 1). For those aberrations that did not introduce phase shifts (VOTF ≈ 1), visual acuity deteriorated due to decreased contrast, which had little effect on VOTF. Therefore it is not surprising to see many of the data points spread horizontally around the VOTF value of 1. Interestingly, we found that good visual acuity was also obtained from some aberration conditions with large phase shifts. Good acuities under these conditions are possible because these large phase shifts resulted in multiple ghost images (e.g. sample images in Figure 1C and D) each of which could be resolved. Such fortuitous legibility is less likely to occur with

Figure 1. Through focus logMAR acuity plots and examples of blurred stimuli. Filled and open symbols show data from two subjects. A: LogMAR visual acuity as a function of Zernike defocus (Z²^0) in the presence of 3 levels of Zernike spherical aberration (Z⁴^0). B: LogMAR visual acuity as a function of normal astigmatism (Z²^±2) in the presence of 2 levels (0.00D, triangles; 0.50D squares) of Zernike vertical coma (Z³^-1). C & D: LogMAR visual acuity as a function of Zernike primary astigmatism (Z²^±2) in the presence of 3 levels (0.10D, triangles; 0.21D, circles; 0.50D, squares) of Zernike secondary astigmatism (Z⁴^±2). Sample stimuli for each aberration conditions are shown at the top of each panel. The defocus or astigmatism level for each stimulus may be read from the abscissa of the corresponding graph. Arrows indicate paraxial focus at each level of higher order aberrations.
Figure 2. Scattergrams showing the correlations between metrics values and logMAR visual acuity measures. Left panels (A, C and E) show examples of three metrics that are well correlated with visual acuity. Straight lines show the slope of orthogonal regression line (i.e. 1st principle component). Right panels (B, D and F) show examples of three metrics that are poorly correlated with visual acuity. Symbols are combined data from the through-focus (filled dots) and the through-astigmatism (open circles) experiments for all four subjects. Each color represents one subject.

Future studies designed specifically to examine the importance of spatial phase might clarify the utility of the metric VOTF for predicting the impact of phase shifts on vision.

We anticipated that objective measures of optical quality that are well correlated with visual acuity are likely to be optimized under the same conditions that optimize visual acuity. To examine this prediction we compared the psychophysically determined through-focus data with computationally generated through-focus plots of each image quality metric. Figure 3 shows an example of such a comparison for 0.21D 2\textdegree. Two examples show that the RMS wavefront error (RMSw) and the PSF half-width-at-half-height (HWHH) are clearly optimized by a defocus level that does not provide maximum acuity. However, visual Strehl ratio (VSOTF) was optimized by almost the exact level of defocus that produced maximum visual acuity. Therefore, if RMSw or HWHH were used as a basis for objective refractions, less than optimal visual acuity would ensue whereas if VSOTF was used, optimal visual acuity would be achieved.
Figure 3. An example of determining subjective best focus and objective best focus. Symbols show logMAR acuity measures (filled dots) and metric values of VSOTF (filled triangles), RMSw (open circles) and HWHH (open triangles) at each through-focus condition. Smooth curves are the 5th order polynomial fit of the logMAR acuity (solid) and each of the three sample metric values (dashed). Arrows indicate best focus that maximize logMAR visual acuity or optimize the metric values.

The analysis shown in Figure 3 was repeated for all 31 metrics, all three levels of fourth order aberration, all three types of aberration, and all subjects. We examined the ability of each metric to accurately predict the subjective best focus in the presence of different levels of fourth order aberrations. The top two panels in Figure 4 compare the optimum level of focus determined subjectively (maximizing visual acuity) with the optimum level determined objectively (optimizing metric). Panel A shows that the three examples of metrics that are well correlated with visual acuity (Figure 2) also predict subjective best focus successfully. The PFSt, STD and VSOTF are all very successful at predicting best sphere power. The slopes of principle component analysis shown in Figure 4A for these three metrics were 1.048, 0.992 and 1.036 and the correlation coefficients were 0.998, 0.999, and 0.998, respectively. Most importantly, the average error in refraction generated by these three objective measures was less than 0.10D. Not surprisingly, panel B shows that the three examples of metrics that were poorly correlated with acuity (Figure 2) were unsuccessful at predicting subjective best focus. Panel B also shows the relationship between paraxial focus and subjective best focus. For each level of 4th order aberration, paraxial focus is consistently hyperopic relative to subjective best focus.

A similar analysis was performed on the through-astigmatism data for the three levels of secondary astigmatism. We have grouped both normal and oblique astigmatism data, which are shown in the bottom two panels of Figure 4. Unlike the sphere data, the same three metrics that were well correlated with logMAR visual acuity were less successful at predicting the optimum astigmatic correction in the presence of secondary astigmatism (Figure 4C). Slopes and correlation coefficients for the astigmatic case are 1.149, 1.189, 1.187, and 0.973, 0.965, and 0.970 for PFSt, STD and VSOTF, respectively. The residual error in astigmatic correction generated by these “good” metrics was, on average 0.13D. By comparison, the errors in spherical and astigmatic correction that would be introduced by the three “poor” metrics were on average 0.53D and 0.26D respectively.

The correlation analysis shown in Figure 2, and the accuracy of the objective sphere and cylinder refractions was assessed for all 31 metrics. The results (R and mean absolute error of residual diopters of sphere and cylinder) are summarized for each metric in Table 1 in the Appendix. Table 1 also shows the refractive accuracy of paraxial focus.

Discussion

The two primary goals of this study were (1) to quantify the impact of fourth order Zernike aberrations (spherical aberration and secondary astigmatism) on subjective best focus, and (2) to identify those objective optical quality metrics that can predict the changes in subjective spherical and cylindrical refractions generated by different levels of the radially symmetric $Z_{40}^0$ and the meridionally varying $Z_{4±2}$. We confirmed that the level of $Z_{40}^0$ and $Z_{4±2}$ had a profound impact on the subjective spherical and cylindrical refraction (Figure 1), and that some but not all objective metrics of optical quality predicted subjective best focus with great accuracy over a wide range of aberration levels (Figure 4 and Table 1).

Although the three objective metrics that were well correlated with visual acuity predicted subjective spherical refractions almost perfectly (Figure 4A), the same metrics
were less accurate for predicting subjective cylinder power (Figure 4C, Table 1). This may reflect a genuine inability of these metrics to predict astigmatic refractions, which in turn, may reflect variability in the response of individual subjects to astigmatic blur. We confirmed that the less accurate objective astigmatic refractions did not reflect higher levels of variability in the original astigmatic acuity data. Examinations of the slopes of the psychometric functions (psychophysical variability) revealed equivalent slopes for spherical and astigmatic defocus.

In an earlier study of monochromatic aberrations in 200 well-refracted adult eyes (Thibos, Hong et al., 2002), we found that subjective best focus was positively correlated with the magnitude of Zernike spherical aberration ($Z_{40}$) and it did not minimize RMS wavefront error. In our simulated aberration paradigm, we also found that subjective refractions (level of positive $Z_{20}^0$ required for maximum acuity) were affected by the levels of $Z_{40}^0$, and maximum acuity was not achieved by minimal RMS. In both studies, acuity was maximized in the presence of positive spherical aberration by a positive $Z_{20}^0$, which was also reported in two studies by Applegate et al. (Applegate, Marsack, & Ramos, 2003; Applegate, Sarver, & Khemsara, 2002). Thus, relative to the defocus that minimizes RMS, both real and virtual eyes were myopic when acuity was maximized. In both cases, this reflects a shift in subjective refraction toward the spherical power required to focus paraxial rays.

In the real eyes of Thibos’ study (Thibos, Hong et al., 2002), subjective spherical equivalents were sufficient to almost perfectly focus paraxial rays from an infinitely distant target (their Figure 15). However, in our virtual eyes, acuity was maximized by spherical equivalents intermediate

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**Figure 4.** Comparison between objective (metric predicted) and subjective determined best focus. Top panels (A, B) show data from through-focus experiment, bottom panels (C, D) show data from through-astigmatism experiment. A & C: Best focus predicted by three metrics (PFSt, solid lines; STD, dashed lines; and VSOTF, dotted lines) that were well correlated with logMAR visual acuity measures. B & D: Best focus predicted by three metrics (RMSw, solid lines; HWHH, dashed lines; and VOTF, dotted lines) that were poorly correlated with logMAR visual acuity measures. Each symbol shows data from one subject at each through focus condition.
to those necessary for minimal RMS (zero $Z_0^0$) and for paraxial focus (zero $r'$) (Figure 1A). This difference may reflect the influence of pupil apodization (Stiles-Crawford effect (Zhang, Ye, Bradley, & Thibos, 1999)), which biases visual responses toward the pupil center (Charman, Jennings, & Whitefoot, 1978; Koomen, Scolnik, & Tousey, 1951; Koomen, Tousey, & Scolnik, 1949; Thibos, Hong et al., 2002) in the real eye subjective refractions. In addition, as argued by Thibos et al (Thibos, Hong et al., 2004), clinical subjective refractions are designed to bring the hyperfocal distance rather than infinity into focus (Figure 5A), therefore coincidentally rendering paraxial rays from an infinite target well focused. This coincidence indicates that half of the depth of focus (dioptic difference between hyperfocal distance and infinity) is approximately equal to the dioptic difference between optimal focus and paraxial focus. However, in the current study, we aimed to maximize visual acuity at a target distance of infinity, therefore the retina is conjugated to a point at infinity, and is conjugated to a point beyond infinity (hyperopia) for paraxial rays (Figure 5B).

If the results of our analysis of 31 image quality metrics performed on our virtual eyes is also observed in real eyes, we would anticipate that subjective refractions would optimize VSOTF and PFSt. Thibos et al (Thibos, Hong et al., 2004) have employed the same 31 metrics to examine the predicted spherical equivalent refractions for the 200 real eyes described in Thibos et al., 2002 (Thibos, Hong et al., 2002). They argue that subjective refractions should optimize vision at the hyperfocal distance, but they did not measure the hyperfocal distance, and thus it is impossible with certainty to identify which metric was actually optimized during the subjective refraction. They found that in order for VSOTF and PFSt to be optimized the target would have to be placed at approximately -0.25 diopters closer than infinity. Of course, this is approximately one half of the depth of focus in front of infinity (Atchison, Charman, & Woods, 1997), that is at the hyperfocal distance. And as described above, the standard maximum plus/minimum minus refraction technique used to generate the subjective refractions is specifically designed to optimize vision at the hyperfocal distance. Therefore, in both our simulated eyes under monochromatic testing and in 200 real eyes refracted in polychromatic light, it appears that some objective image quality metrics (e.g., VSOTF and PFSt) are optimized when visual acuity is maximized.

The discrepancies seen between the subjective refraction in our computational “virtual eye” and those of real eyes (the latter approximates a paraxial refraction), emphasize that the objective metrics that were so accurate at predicting refractions in our study may systematically over-minus the patient. This discrepancy will likely be larger for larger pupils. Therefore, a successful implementation of aberrometry for autorefraction may require the inclusion of an apodized pupil into the computational algorithms (Thibos, Hong et al., 2002) and consideration of the maximum plus/minimum minus philosophy employed during subjective refractions.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Schematics showing A: In Thibos’ study, clinical subjective refractions conjugate the retina to the hyperfocal plane that is 1/2 depth of field in front of infinity, and is in between the retina conjugate plane for paraxial focus and minimum RMS. B: In current study, optimum refraction is achieved when the retina is conjugated to infinity, and again in between paraxial focus and minimum RMS. Any objective image quality metric (e.g., VSOTF) that accurately predicted subjective best focus would conjugate the retina to infinity.


Appendix

Table 1 and a simple clarification of the acronyms of the metrics (Table 2) are provided below.

<table>
<thead>
<tr>
<th>Metric #</th>
<th>Metric acronym</th>
<th>R</th>
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<th>Astigmatic error (D)</th>
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<td>1</td>
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<td>0.4931</td>
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<td>18</td>
<td>PS(8): STD</td>
<td>-0.8158</td>
<td>0.0483</td>
<td>0.1408</td>
</tr>
<tr>
<td>19</td>
<td>PS(9): ENT</td>
<td>0.7198</td>
<td>0.6217</td>
<td>0.3358</td>
</tr>
<tr>
<td>20</td>
<td>PS(10): NS</td>
<td>-0.8464</td>
<td>0.0283</td>
<td>0.1242</td>
</tr>
<tr>
<td>21</td>
<td>PS(11): VSX</td>
<td>-0.7942</td>
<td>0.075</td>
<td>0.1625</td>
</tr>
<tr>
<td>22</td>
<td>SF(1): SFcMTF</td>
<td>-0.5333</td>
<td>0.1683</td>
<td>0.4175</td>
</tr>
<tr>
<td>23</td>
<td>SF(2): AreaMTF</td>
<td>-0.7445</td>
<td>0.035</td>
<td>0.1508</td>
</tr>
<tr>
<td>24</td>
<td>SF(3): SFcOTF</td>
<td>-0.6416</td>
<td>0.1583</td>
<td>0.2308</td>
</tr>
<tr>
<td>25</td>
<td>SF(4): AreaOTF</td>
<td>-0.7671</td>
<td>0.0317</td>
<td>0.1442</td>
</tr>
<tr>
<td>26</td>
<td>SF(5): SROTF</td>
<td>-0.6542</td>
<td>0.3917</td>
<td>0.1608</td>
</tr>
<tr>
<td>27</td>
<td>SF(6): VOTF</td>
<td>-0.1815</td>
<td>0.385</td>
<td>0.1975</td>
</tr>
<tr>
<td>28</td>
<td>SF(7): VSOTF</td>
<td>-0.8216</td>
<td>0.0717</td>
<td>0.1508</td>
</tr>
<tr>
<td>29</td>
<td>SF(8): VNOTF</td>
<td>-0.2938</td>
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<td>0.4992</td>
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<tr>
<td>30</td>
<td>SF(9): SRMTF</td>
<td>-0.7658</td>
<td>0.3883</td>
<td>0.2625</td>
</tr>
<tr>
<td>31</td>
<td>SF(10): VSMTF</td>
<td>-0.8456</td>
<td>0.075</td>
<td>0.1542</td>
</tr>
<tr>
<td>32</td>
<td>Paraxial</td>
<td>0.525</td>
<td>0.5925</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Correlation coefficients (metrics values vs. logMAR acuity measures, R) and mean absolute spherical (SE) and astigmatic errors between subjective and objective best focus for each of the 31 objective image quality metrics (Thibos, 2003). Shadowed metrics were the ones used as examples in the text. Metrics in red indicate poor correlations with logMAR visual acuity, whereas metrics in blue indicate good correlations with logMAR visual acuity. The errors produced by paraxial focus are also included.
WF(1): RMSw = root-mean-squared wavefront error computed over the whole pupil (microns)
WF(2): PV = peak-to-valley difference (microns)
WF(3): RMSs = root-mean-squared wavefront slope computed over the whole pupil (arcmin)
WF(4): PFWc = pupil fraction when critical pupil is defined as the concentric area for which RMSw < criterion (e.g. wavelength/4)
WF(5): PFWt = pupil fraction when a "good" sub-aperture satisfies the criterion PV < criterion (e.g. wavelength/4)
WF(6): PFSt = pupil fraction when a "good" sub-aperture satisfies the criterion horizontal slop and vertical slop are both < criterion (e.g. 1 arcmin)
WF(7): PFSc = pupil fraction when critical pupil is defined as the concentric area for which RMSs < criterion (e.g. 1 arcmin)
WF(8): Bave = average blur strength (diopters)
WF(9): PFCt = pupil fraction when a "good" sub-aperture satisfies the criterion Bave < criterion (e.g. 0.25D)
WF(10): PFCc = pupil fraction when critical pupil is defined as the concentric area for which Bave < criterion (e.g. 0.25D)
PS(1): D50 = diameter of a circular area centered on peak which captures 50% of the light energy (arcmin)
PS(2): EW = equivalent width of centered PSF (arcmin)
PS(3): SM = square root of second moment of light distribution (arcmin)
PS(4): HWHH = half width at half height (arcmin)
PS(5): CW = correlation width of light distribution (arcmin)
PS(6): SRX = Strehl ratio computed in spatial domain
PS(7): LIB = light-in-the-bucket
PS(8): STD = standard deviation of intensity values in the PSF, normalized to diffraction-limited value
PS(9): ENT = entropy of the PSF
PS(10): NS = Neural sharpness
PS(11): VSX = visual Strehl ratio computed in the spatial domain
SF(1): SFcMTF = spatial frequency cutoff of radially-averaged modulation-transfer function (rMTF)
SF(2): AreaMTF = area of visibility for rMTF (normalized to diffraction-limited case)
SF(3): SFcOTF = spatial frequency cutoff of radially-averaged optical-transfer function (rOTF)
SF(4): AreaOTF = area of visibility for rOTF (normalized to diffraction-limited case)
SF(5): SROT = Strehl ratio computed in frequency domain (OTF method)
SF(6): VOTF = volume under OTF normalized by the volume under MTF
SF(7): VSOTF = visual Strehl ratio computed in frequency domain
SF(8): VNOTF = volume under neurally-weighted OTF, normalized by the volume under neurally weighted MTF
SF(9): SRMTF = Strehl ratio computed in frequency domain (MTF method)
SF(10): VSMTF = visual Strehl ratio computed in frequency domain (MTF method)

Table 2. Acronyms of the metrics.
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References


