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Retinal image quality for virtual eyes generated by a statistical model of ocular wavefront aberrations

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Abstract

A statistical model of the aberration structure of normal, well-corrected eyes was developed previously (*Opthal. Physiol. Opt* **22**, 427–433, 2002.) from wavefront aberrations measured for 100 normal eyes (*J. Opt. Soc. Am. A.* **19**, 2329–2348, 2002.). The model is capable of generating an unlimited number of wavefront aberration functions for virtual eyes drawn randomly from a multivariate Gaussian distribution of Zernike aberration coefficients. This report provides evidence that monochromatic retinal image quality in virtual eyes, as quantified by 31 different image quality metrics (*J. Vis.* **4**, 329–351, 2004.), is representative of human eyes but slightly exaggerates the degradation of the retinal image caused by ocular aberrations. A demonstration program for producing virtual eyes is included as an Appendix to this paper.

Keywords: eye models, image quality, schematic eyes, wavefront error

Introduction

Traditionally, schematic eye models have had fixed properties that represent the optical features of the average human eye (Smith, 1995). In an attempt to capture the rich variation between individuals, a statistical model of the aberration structure of normal, well-corrected eyes was developed previously (Thibos *et al*., 2002a) to generate virtual eyes that have the same optical properties (on average) as normal eyes. That statistical model is capable of generating an unlimited number of unique wavefront aberration functions drawn randomly from a multivariate Gaussian distribution that characterizes the sample population in the Indiana Aberration Study (Thibos *et al*., 2002b). One application of the model has been to predict the performance of deformable mirrors used in adaptive optics systems for correcting the higher-order aberrations of the eye (Dalimier and Dainty, 2005; Kennedy and Paterson, 2007). Another potential application is the study of individual variation in retinal image quality. Such an application requires evidence that the image quality of virtual eyes produced by the model is representative of the image quality of human eyes. In the present study I sought the necessary evidence by computing 31 different image quality metrics (Thibos *et al*., 2004) for 100 human eyes in the Indiana Aberration Study and also for 1000 virtual eyes created by the statistical model. The results show that a multivariate Gaussian statistical model of wavefront aberrations provides realistic values of image quality metrics that are representative of human eyes, but slightly exaggerates the degradation of the retinal image caused by ocular aberrations.

The approach to eye models embodied in this study is atypical. Most schematic eyes described in the visual optics literature place high priority on anatomical accuracy, but such models require substantial optical analysis using sophisticated ray-tracing computer software to establish a link between structure and function. In contrast, the statistical approach adopted here defines the eye model mathematically with a wavefront aberration function (WAF) rather than a physical arrangement of optical elements. Thus virtual eyes are functional

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models rather than mechanistic models of the eye's optical system. One advantage of this approach is that a direct link is established between the model's specifications and the retinal image through the traditional methods of Fourier optics (Goodman, 1968). Another advantage is that the model is conceived from the outset as a stochastic process, rather than a system with fixed parameters, so that individual variation becomes an inherent feature of the model.

Methods

The individual variation in wavefront aberration functions (WAFs) modeled by virtual eyes (Thibos *et al.*, 2002a) mimics the variation observed in the Indiana Aberration Study of normal eyes (Thibos *et al.*, 2002b). That normative study employed a Shack–Hartmann wavefront sensor to measure WAFs for 633 nm light along the primary line-of-sight of 200 healthy eyes from 100 individuals for a 6 mm pupil. Most subjects were optometry students in the age range 22–35 years. Accommodation was paralyzed and sphero-cylindrical refractive errors were corrected with trial lenses for aberrometry. Small residual refractive errors were inevitable because the lenses were quantized in 0.25D steps, but otherwise we think of these eyes as being well-corrected by normal clinical standards.

A Zernike expansion represents each WAF by a weighted sum of Zernike polynomials,

$$W(x,y) = \sum_{n,m} c_n^m Z_n^m(x,y), \tag{1}$$

where $W(x, y)$ is the wavefront defined over the x,y coordinates of the pupil, c_n^m are the aberration coefficients, and $Z_n^m(x, y)$ are the Zernike polynomials of order n and meridional frequency m. Thus, a vector of Zernike aberration coefficients associated with an individual WAF is a compact way of describing the aberration structure of any individual eye. For a population of eyes, each Zernike coefficient c_n^m is a random variable that is correlated to some degree with every other Zernike coefficient of some other order or meridional frequency. For the population of normal eyes measured in the Indiana Aberration Study, each individual Zernike coefficient was reasonably well described as a Gaussian random variable with a mean and variance determined experimentally. Based on these results, it was assumed (Thibos *et al.*, 2002a) that the vector of 36 aberration coefficients representing $n = 7$ Zernike orders could be adequately described as a multivariate Gaussian random process. One appealing feature of a multivariate Gaussian model is its simplicity. The statistical structure of such a model is fully defined by the means and variances of the various Zernike modes and by the covariance between all possible pairs of modes. The numerical values of these parameters are conveniently represented by a vector of mean values and a variance-covariance matrix. A demonstration program (for MatLab, by The Math Works, Inc., Natick, MA, USA) for producing virtual eyes is included as 'Supporting Information' to this paper.

For each vector of Zernike coefficients representing a single eye, 31 different scalar metrics of retinal image quality for monochromatic (633 nm) light were computed using the methods described in detail elsewhere (Thibos *et al.*, 2004). Metrics were computed for the 100 human right eyes of the Indiana Aberration Study and for 1000 virtual eyes created by our statistical model. These metrics represent a variety of ways to quantify the eye's optical quality based on the wavefront aberration function (WAF), the point-spread function (PSF), and the optical transfer function (OTF). Some metrics are purely optical in nature whereas others quantify visual quality by weighting the retinal image with a neural transfer function. Some of these metrics increase when image quality improves, but other metrics decrease. For convenience of reporting, the computed results were converted into metrics of image degradation (ID) that always increase in value when the image deteriorates.

Results

Frequency distributions for all 31 metrics of image degradation are shown in *Figure 1* for 100 human eyes (blue bars) and for 1000 virtual eyes (solid red lines). Each panel also shows the mean and standard deviation of the metric for both populations. For any given metric, frequency histograms for metric values were similar in shape, mean, and variance for the virtual and human populations. However, most metrics indicated that the retinal image is more degraded in virtual eyes than in human eyes (10% difference on average).

The discrepancy between mean values of image degradation for human and virtual eyes is shown in two ways in *Figure 2*. The abscissa displays the discrepancy as a fraction of the mean value for the human population. The ordinate displays the discrepancy relative to the standard error of the mean value for the human population. Thus the ordinate can be interpreted as a t-statistic for testing the hypothesis that the human and virtual populations have the same mean. Values of $t > 2$ are statistically significant at the 5% level, so symbols lying above the dashed line represent evidence that the means differ significantly. A majority of symbols lie above the dashed line and for those metrics the mean discrepancy is 9%. This majority group of symbols includes metrics derived from all three categories of wavefront error (WFE), point-spread function (PSF), and optical transfer function (OTF) analysis.

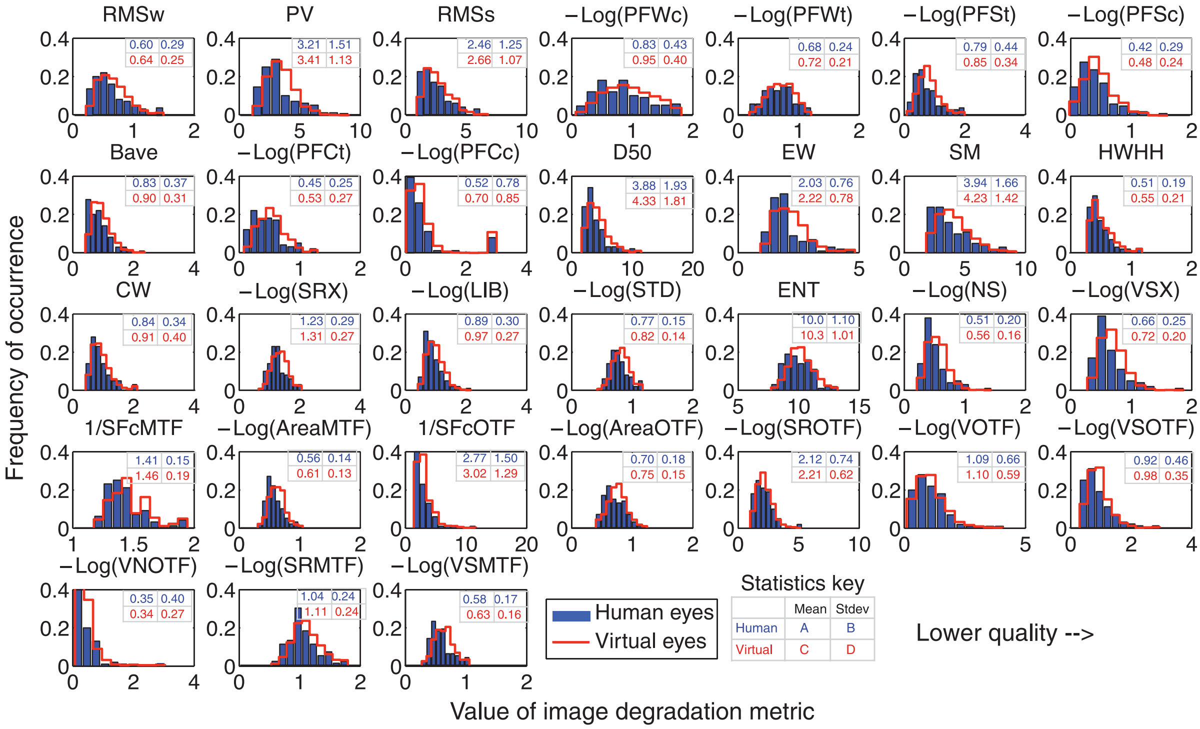

Figure 1. Frequency histograms of image degradation metrics for a normal population of 100 human eyes (shaded bars) and for a population of 1000 virtual eyes created by a statistical model (solid lines). Acronyms refer to metrics of image quality defined elsewhere (Thibos *et al.*, 2004). Title of each histogram indicates how image degradation was derived from published metrics. Each panel shows the mean and standard deviation of the metric for both populations. Pupil diameter = 6 mm.

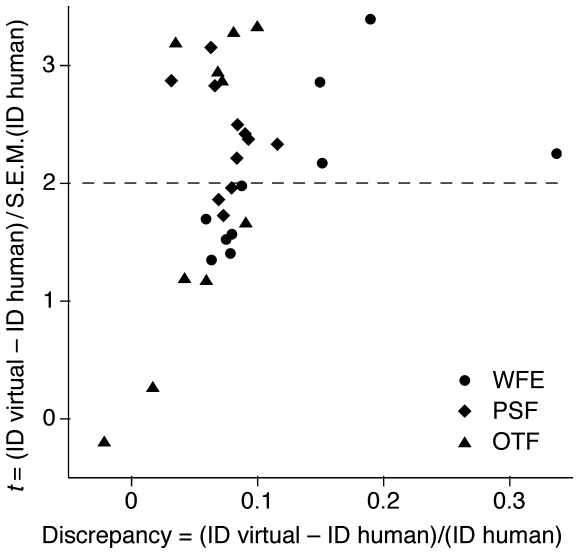

Figure 2. Scattergram of discrepancy between mean values of image degradation (ID) for human and virtual eyes (abscissa) against a *t*-statistic associated with that discrepancy (ordinate). Symbols represent results from metrics based on wavefront error (WFE, circles), point-spread functions (PSF, diamonds), and optical transfer functions (OTF, triangles). A majority of metrics indicated a statistically significant excess of image degradation in virtual eyes relative to human eyes.

I conclude from these results that the multivariate Gaussian model of wavefront aberrations provides realistic values of image degradation metrics that are representative of human eyes, but tends to slightly overestimate the degradation of the retinal image produced by ocular wavefront aberrations.

Discussion

A variety of potential applications are likely to benefit from a statistical model of the eye's optical aberrations. For example, virtual eyes may be useful for computer simulation of individual variation in aberration structure, retinal image quality, visual performance, or response to optical treatment. For each virtual eye, we can compute the corresponding point-spread function (PSF), optical transfer function (OTF), or retinal image for an arbitrary object. From each of these functions we may compute summary metrics of image quality that can be used to predict visual performance for tasks such as visual acuity, contrast sensitivity, or target detection (Cheng *et al.*, 2004; Marsack *et al.*, 2004; Pesudovs *et al.*, 2004; Williams *et al.*, 2004; Applegate *et al.*, 2006). Before following this path, however, it is important to verify that the PSFs and OTFs produced by the statistical model are representative of human eyes. The current results demonstrate that for a broad spectrum of image quality metrics commonly used to predict visual performance, virtual eyes are similar to human eyes but slightly over-estimate the degradation of the image quality caused by ocular aberrations.

The cause of over-estimation of image degradation by the model is unknown, but is likely due to a departure of human eyes from the multivariate Gaussian behavior assumed by the statistical model. One way to test this idea is to compare two different populations of virtual eyes (500 eyes in each population), both drawn at random using the same statistical model. When this comparison was made, unlike the comparison between real and virtual eyes described in Results, none of the metrics of image degradation was significantly different for the two populations. This result shows that the source of the discrepancy between real and virtual eyes is not due to random variation *per se*, or to the specific details of the computer implementation of the model. Instead, it appears that some metrics are particularly sensitive to the failure of a Gaussian model to capture completely the statistical variation in aberration structure of real eyes. This failure reaches statistical significance for a moderate-sized population (100 human eyes) because the mean discrepancy is large relative to the standard error.

In a clinical context, a population of virtual eyes may prove useful for predicting the fraction of individuals who will benefit from new designs of ophthalmic lenses or instruments. Given a model of how such ophthalmic devices interact with the eye to produce a complete optical system, alternative system designs might be tested against a large number of virtual eyes, thereby reducing the need for costly clinical trials. The present results provide support for those applications by demonstrating that virtual eyes have retinal image quality that is similar to image quality in human eyes. Since virtual eyes exaggerate image degradation, they represent a slightly more stringent challenge for wavefront correction and imaging technologies.

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Supporting information

Additional Supporting Information may be found in the online version of this article:

Program S1. Demonstration program for producing virtual eyes (zip file).

Please note: Wiley- Blackwell are not responsible for the content or functionality of any supporting materials provided by the author. Any queries (other than missing material) should be directed to the corresponding author for the article.

References

Applegate, R. A., Marsack, J. D. and Thibos, L. N. (2006) Metrics of retinal image quality predict visual performance in eyes with 20/17 or better visual acuity. *Optom. Vis. Sci.* **83,** 635–640.

Cheng, X., Bradley, A. and Thibos, L. N. (2004) Predicting subjective judgment of best focus with objective image quality metrics. *J. Vis.* **4,** 310–321.

Dalimier, E. and Dainty, C. (2005) Comparative analysis of deformable mirrors for ocular adaptive optics. *Opt. Express* **13,** 4275–4285.

Goodman, J. W. (1968) *Introduction to Fourier Optics*, New York, McGraw-Hill.

Kennedy, G. T. and Paterson, C. (2007) Correcting the ocular aberrations of a healthy adult population using microelectromechanical (MEMS) deformable mirrors. *Opt. Commun.* **271,** 278–284.

Marsack, J. D., Thibos, L. N. and Applegate, R. A. (2004) Metrics of optical quality derived from wave aberrations predict visual performance. *J. Vis.* **4,** 322–328.

Pesudovs, K., Marsack, J. D., Donnelly, W. J. ,III, Thibos, L. N. and Applegate, R. A. (2004) Measuring visual acuity – mesopic or photopic conditions, and high or low contrast letters? *J. Refract. Surg.* **20,** S508–S514.

Smith, G. (1995) Schematic eyes: history, description and applications. *Clin. Exp. Optom.* **78,** 176–189.

Thibos, L. N., Bradley, A. and Hong, X. (2002a) A statistical model of the aberration structure of normal, well-corrected eyes. *Ophth. Physiol. Opt.* **22,** 427–433.

Thibos, L. N., Hong, X., Bradley, A. and Cheng, X. (2002b) Statistical variation of aberration structure and image quality in a normal population of healthy eyes. *J. Opt. Soc. Am. A.* **19,** 2329–2348.

Thibos, L. N., Hong, X., Bradley, A. and Applegate, R. A. (2004) Accuracy and precision of objective refraction from wavefront aberrations. *J. Vis.* **4,** 329–351.

Williams, D. R., Applegate, R. A. and Thibos, L. N. (2004) Metrics to predict the subjective impact of the eye's wave aberration. In: *Wavefront Customized Visual Correction: The Quest for Super Vision II* (eds R. R. Krueger, R. A. Applegate and S. M. Macrae), Thorofare, NJ, Slack, pp. 78–84.