Limits to Vision: Can We Do Better Than Nature?

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ABSTRACT

Non-invasive wavefront sensing of the human eye provides the necessary information to design corrections which minimize the monochromatic optical errors of the eye beyond simple sphere (defocus) and cylinder (astigmatism). These "ideal" corrections must move with the eye, maintaining proper alignment with the eye's optics. Viable modes of correction include contact lenses, refractive surgery and intraocular lenses. Will these "ideal" corrections lead to better vision? If so, how much better? Here we explore the limits imposed by the optical and neural design of the eye. For larger pupil sizes (>3 mm diameter) "ideal" corrections improve the optical quality of the retinal image beyond the limits imposed by photoreceptor spacing. Photoreceptor spacing limits visual acuity to between 20/8 and 20/10. Correcting the higher order aberrations will provide images with higher contrast and crisper edges. When perfected, "ideal" corrections will provide for high contrast visual acuity between 20/8 and 20/10. [*J Refract Surg* 2000;16:S547-S551]

BACKGROUND

Can the retinal image be improved, and if so, will we see we better? To answer these questions, it is necessary to explore the limits imposed by the optical and neural design of the eye.

What is an "ideal" optical correction? Clinically, we generally define the optical correction to be the sphero-cylindrical correction providing the best visual acuity for distance vision. We then modify this correction to suit the patient's particular needs and prescribe, most commonly in the form of: spectacles, contact lenses, intraocular lenses, and refractive surgery. These corrections are designed to eliminate the sphero-cylindrical refractive error of the eye. They are not "ideal" corrections. That is, current modes for correcting the optical aberrations of the eye do not reduce the higher order aberrations of the eye (Figs 1A-D).

Although it is possible to design and implement compensating optics that reduce the eye's higher order optical aberrations, the question remains: Can the neural retina capitalize on the increased image detail?

LIMITS IMPOSED BY THE NEURAL RETINA

Unlike the film plane of the camera, the "grain" of the neural retina is not uniform. The 0.35 mm diameter foveola (0.385 mm^2 or approximately 1 degree) has the highest packing density of cones and is the area of the retina that provides the normal fixating eye with its highest spatial resolving ability (Fig 2). As the distance from the foveola increases, cone density decreases and the spatial resolving ability of the neural retina decreases. As a consequence, the optical quality of the retinal image needs to be optimized over the small area of the foveola. Optimal imaging over a small area is a simpler optical problem than maintaining an optimized image over the approximately 840 mm^2 image plane of a 35 mm camera. On the other hand, biomechanical variability between individuals and variation of the optical properties of the eye over time complicate implementing a onetime permanent correction.

Within the foveola, the diameter of the cone photoreceptors limits the neural retina's ability to sample the retinal image. In the foveola the cones are long, narrow, and closely packed having a diameter on the order of 2 µm.[1] The problem of sampling induced by receptor size and packing can be seen in Figure 3. If the eye's optics could image a letter "E" within the entrance aperture of a single cone, the letter "E" could not be differentiated from a period (Fig 3A). To be seen as a letter "E", the letter must cover a sufficient number of cones to allow the letter to be differentiated into its component parts (Fig 3B).

The exact limit to visual acuity is not as important as understanding that the visual acuity is limited by receptor diameter, receptor packing, and

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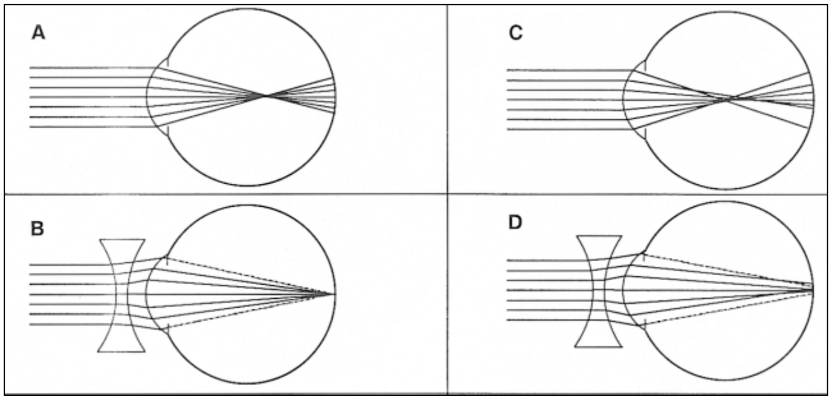

Figure 1. A) Displays the typical cartoon explanation of myopia, and **B)** its correction. **C)** An exaggerated cartoon of myopic reality, and **D)** its correction. Here, light from a distant point source sort of comes to a focus in front of the retina (C) and the optimal spectacle correction moves "the sort of point image" back to the retina. That is, the optimal sphero-cylindrical correction does not eliminate the eye's higher order optical aberrations.

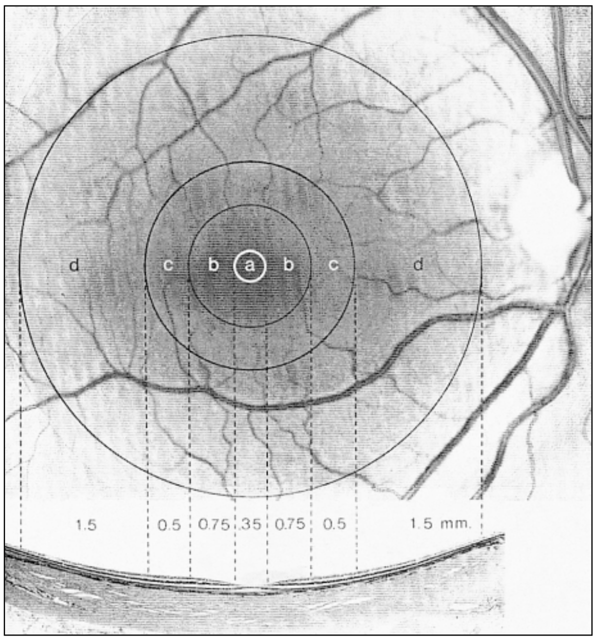

Figure 2. An anatomical view of the macular region as viewed from the front and in cross section (below). a) foveola, b) fovea, c) parafoveal area, d: perifoveal area. (With permission from Histology of the Human Eye, by Hogan, Alvarado and Weddell, W.B. Saunders Company, 1971, page 491.)

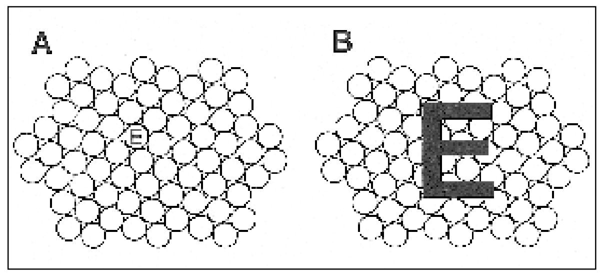

Figure 3. A) If a letter "E" is imaged such that it falls within the borders of a single photoreceptor, then the letter "E" cannot be differentiated from a period. **B)** To be seen as a letter, "E" must be sampled by enough photoreceptors to differentiate the letter's component parts.

biological variation (which causes the exact limit to vary between individuals over a limited range). If we assume that the average foveola cone is on the order of 2 to 2.5 µm (the center to center distance between cones is between 2 and 3 µm), and that the secondary nodal distance for the emmetropic eye is 16.67 mm, then receptor packing limits visual acuity to between 20/10 and 20/8 (60 and 75 cycles/degree). The retina is in constant motion (dithering), moving the retinal image over several receptors. Such movement will likely improve the neural limits of photoreceptor sampling slightly.

The fact that receptor sampling limits visual acuity does not mean that targets smaller than the limit are invisible. If there is sufficient contrast, targets smaller than 20/8 can be seen in an alias form[2], distorted from under sampling (Fig 4).

Retinal image quality and the neural limit imposed by the diameter of the foveolar cones are not the only factors that influence and/or limit our visual percept. If the neural portion of the visual system is not exposed to good retinal images early in life, visual performance will be reduced resulting in refractive amblyopia.[3] The fact that refractive amblyopia exists leads to the interesting question: Will a person with 20/20 best corrected be able to see 20/8 if the retinal image is optimized later in life? I believe visual acuity will improve but not necessarily to retinal limits. Refractive amblyopia generally improves one or more lines of acuity when the refractive error is eliminated and can improve more over time. Expanding the concept of amblyopia slightly, one can't help but wonder if we had a much better retinal image early on (within the first year), if the potential for unrealized functional improvements in visual processing might be realized.

Visual performance in the real world is further complicated by factors that include past visual

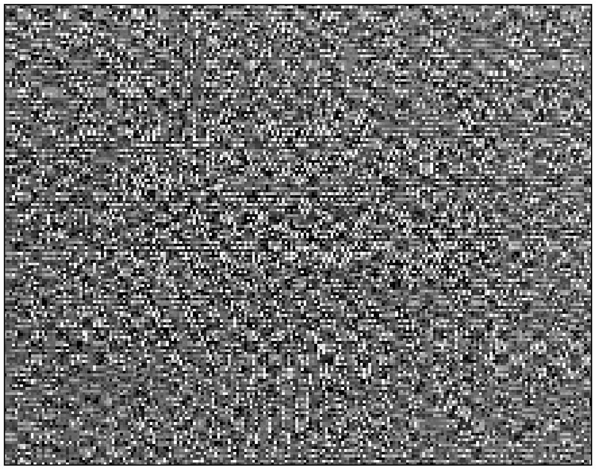

Figure 4. A simulated retinal view of an 80 cycle/degree grating (notice the edges of the pattern shows the grating) being sampled by a primate foveolar retinal receptor mosaic. Undersampling creates an alias percept of the grating that appears as zebra stripes. Courtesy of David Williams.

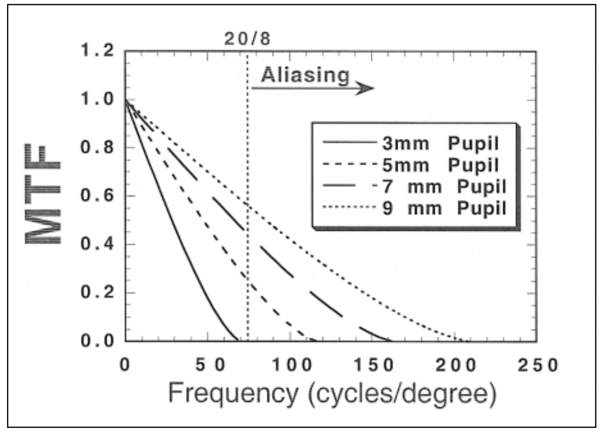

Figure 5. Diffraction limited modulation transfer functions (wavelength 555 nm) for the eye at 4 different pupil sizes (3, 5, 7 and 9 mm). The vertical line at 75 cycles/degree (20/8 Snellen equivalent) represents the upper limit of adequate photoreceptor sampling to properly recognize the grating. Calculated using formulas presented in Smith's textbook[10] and parameters of the Gullstrand exact schematic eye.

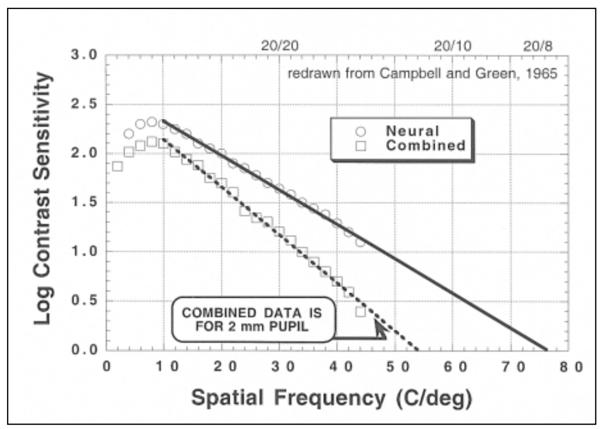

Figure 6. A reconstruction of the data presented by Campbell and Green in 1965.[6] The upper data set (open circles) represents the neural contrast sensitivity function for a normal eye. An extrapolation of the data reveals a cut-off frequency very near 75 cycles/degree the limit imposed by foveolar photoreceptor diameters. The lower data set (open squares) represents the combined optical and neural contrast sensitivity function of the normal eye for a 2 mm pupil diameter in monochromatic light. An extrapolation of the data reveals a cut-off frequency very near 47 cycles/degree, which is very near the diffraction limit imposed by the 2 mm pupil used in their study. Both curves are reasonably well predicted by theory.

experience, cognitive ability, expectation, and information content. As is common knowledge in sports vision circles: Excellent hitters in baseball, generally have very good visual acuity. The converse is not necessarily true. Good visual acuity, does not mean one will be a good hitter.

LIMITS IMPOSED BY THE EYE'S OPTICS

Improving the optics of the eye by removing aberrations increases the contrast and spatial detail of the retinal image. These effects are pupil dependent. The larger the pupil in a diffraction limited system, the higher the contrast and the crisper the edges of the retinal image.[4,5] As can be seen in Figure 5, the diffraction limited modulation transfer function (MTF) for 555 nm monochromatic light monotonically increases as pupil size increases for all spatial frequencies greater than zero. Also note, the cut-off spatial frequency of the MTF (the spatial frequency at which the modulation transfer goes to zero) linearly increases with pupil size.

For pupils larger than 3 mm, aliasing from under sampling can occur and can be significant for larger pupil sizes. However, the gains in contrast with increasing pupil size are largest for spatial frequencies less than 75 cycles/degree. Consequently, the disadvantages of aliasing for everyday vision are likely to be small compared to the gains in contrast and detection.

Does theory agree with actual measures of visual performance? In 1965, Campbell and Green[6] reported measurements of the monochromatic modulation transfer function of the eye using two different psychophysical techniques. One (neural-limited) that bypassed the optics of the eye and imaged gratings onto the retina using interference techniques and a second free viewing technique that included the optics of the eye. As can be seen in Figure 6, extrapolation of neural limited data reveals cut-off frequency of about 75 cycles/degree, almost exactly at the theoretical sampling limit imposed by photoreceptor diameter. Extrapolation of the free viewing data set reveals a cut-off frequency close to the theoretical limit imposed by the 2 mm artificial pupil (47 cycles/degree) used in the study.

DISCUSSION

I have limited this review to monochromatic aberrations at a fixed viewing distance. It is important to remember that as viewing distance changes so does the ideal compensating optic. Consequently, no one compensating optic can be made or carved into the cornea that will optimally correct the eye for all viewing distances. Likewise, the world is polychromatic and not monochromatic. Consequently, the eye's resolution limits will be reduced over the monochromatic estimates presented above, due to the eye's chromatic aberrations.

Although viewing distance and chromatic aberrations are important factors that will degrade retinal image, it is important to realize that natural biological variation has provided the world with eyes that approach the theoretical limits imposed by receptor sampling (between 20/8 and 20/10). Consequently and to the extent that retinal image quality has reduced visual performance from what the neural system is capable of processing, improving the optics will improve visual performance.

So can we do better than nature? We already do! Spectacles, contact lenses, IOLs, refractive surgery, more often than not, improve on nature (at least for those of us who are ametropic). The more significant question is, can an ideal compensating optic based on wavefront measurements provide better vision than sphero-cylindrical corrections? I offer the following answer. If a patient is best corrected with sphero-cylindrical lenses to 20/10 or better, reducing the higher order aberrations will most likely not improve high contrast acuity but will increase perceived contrast. If on the other hand, a patient's best correction with sphero-cylindrical is limited to 20/25 or 20/20 due to optical aberrations in an otherwise normal eye, then yes—reducing the higher order aberrations will improve visual performance as measured by visual acuity (or for that matter any other measure of spatial vision). In all cases eliminating the sphero-cylindrical error of the eye and reducing the higher order aberrations will increase image contrast. Objects in the visual world will have higher contrast and crisper borders. Measurements on subjects whose higher order aberrations were corrected with a deformable mirror have shown improvements in both acuity and contrast sensitivity.[4,7] Most patients, but certainly not all, will prefer the gain in contrast and sharper borders. However, some patients will prefer a softer view of the world offered by lower contrast and blurred edges. In the slightly longer run as the industry learns how to better implement optical corrections that reduce the higher order aberration of the eye, I believe that corrections will be designed that routinely improve vision to 20/10.

LOOKING INTO THE EYE

So far, this paper has focused on improving vision to physiological limits. Reducing the optical aberration of the eye not only improves vision, but also improves our ability to see into the eye. Improving the view into the eye is particularly exciting because it is not limited by photoreceptor sampling characteristics, but instead by the optics of the eye and the optics and sensors designed to do the looking. For example, adaptive optics in the form of deformable mirrors have improved the view into the eye such that individual photoreceptors can be photographed non-invasively in the living eye.[8,9] In the near future, these tools will provide new insights into the natural history of ocular disease, earlier detection, and an effective method to monitor therapy prior to a visual acuity loss.

REMAINING QUESTIONS

For corneal refractive surgery, the major issues will center on minimizing adverse biomechanical effects induced by the surgery and individual variability in the response to surgery. To the extent the adverse corneal responses to surgery are predictable across the patient population, adaptations to the surgery should be able to reduce or eliminate the unwanted response. For unpredictable adverse responses, a better understanding of individual biomechanical responses is needed. The jury is out in defining the line between predictable and unpredictable adverse responses. Certainly, paying attention to physiologic pupil size and minimizing the abrupt transitions within the pupil has led to improved surgery, and early data from wavefront guided ablations is encouraging.

For contact lenses, issues will center on acceptability of the modality (as a rule, people would like to be aid-free) and maintaining proper registry of the contact lens with the optics of the eye. Contact lenses have the distinct advantage that they can be easily changed, refined over time and that contact lens failure has no permanent consequence.

For IOLs, issues will center on materials and methods to refine the correction once in place. The method and quality with which IOLs are manufactured are reasonably easy to control. IOLs could be designed and constructed to minimize the aberrations of the eye. But exact placement will be difficult. However, if the IOL is designed and constructed in a clever way, we should be able to perform the ultimate "touch-up" once the lens is placed in the eye. For instance, imagine a lens material that can change index locally when activated by a control beam, or a lens that can be ablated once in place, or, put simply, a human made IOL is not subject to bio-variability and could reasonably be designed to allow for the ultimate "touch-up" once in place. It also provides a vehicle for future non-invasive tune-ups as the eye's optical properties change with age.

As a clinicians know from practice, patients are willing to lose a small amount of visual function in order to be aid-free. Being aid-free is a strong driving force. Nonetheless, it is my prediction that patients will prefer, seek out, and pay for higher contrast and crisper edges provided by corrections that reduce the eye's higher order aberrations in an aid-free manner.

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