

References

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Optimal Vision: Blurring and Aliasing

In his article "Retinal Imaging and Vision at the Frontiers of Adaptive Optics" (*PHYSICS TODAY*, January, page 31), Donald T. Miller shows that it is possible to improve the resolution, contrast, and clarity of retinal images by correcting for defects in the eye's optics. We agree that "the best retinal image quality is obtained with the largest physiological pupil diameter (8 mm) and with full correction of all ocular aberrations." However, we disagree with Miller's suggestion that the quality of vision may be improved similarly (to achieve "supernormal vision") if the eye's optics could be "corrected" with "adaptive optics" to produce the performance of an aberration-free 8-mm lens.

The angular spacing between retinal photoreceptors, as Miller states, "represents a neural limitation to visual resolution." In terms of communication theory, this spacing determines the sampling passband of the eye that, analogous to the bandwidth of a communication channel, sets an upper bound on the highest spatial frequencies that the eye can convey to the higher levels of the brain. The preferred modulation transfer function (MTF)—or spatial frequency response—of the eye's optics relative to this sampling passband is inescapably a compromise between blurring and aliasing. Because the MTF decreases smoothly with increasing frequency, aliasing can be substantially decreased only at

the cost of blurring and vice versa.

If blurring and aliasing are properly accounted for in terms of their effect on the information rate that the eye conveys to the higher levels of the brain, then it is the MTF of the 3-mm lens rather than that of the 8-mm lens that, in normal daylight, maximizes this rate for the 50 cycles/degree sampling passband of the eye.¹ Hence, communication theory and evolution converge, under appropriate conditions, toward the same optical design. And why not? It seems unlikely that evolution would have missed the opportunity to improve our vision if it could have done so merely by permitting the pupil to be wider than 3 mm during normal daylight conditions.

Reference

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MILLER REPLIES: Friedrich Huck and Carl Fales raise valid concerns about realizing supernormal vision. These concerns, however, are also expressed in my article. The neural system will ultimately limit the degree of supernormal vision that may be achieved after the aberrations in the eye are corrected. In my article I state, "In an eye with perfect optics, visual performance becomes constrained by neural factors, specifically the spacing between retinal photoreceptors, which represents a neural limitation to visual resolution that is only slightly higher than the normal optical limit." I go on to say that this would lead to aliasing, which would degrade vision.

Optimal vision then becomes a compromise between blurring and aliasing. But what constitutes optimal vision and what compromise is appropriate for achieving it? These are difficult questions that the vision community continues to address. Currently, our understanding of the limits placed on vision by the retina and visual pathways of the brain are not sufficient to provide universal answers to these questions. The search for answers is further complicated because visual performance is heavily task-dependent. Visual per-

formance for some specialized tasks will probably decline with adaptive optics. For example, when observers viewed a steady point source through adaptive optics, it sometimes appeared green and sometimes red, depending on which photoreceptor type the light was stimulating. With more natural stimuli, however, subjects have regularly experienced a strikingly crisp appearance consistent with the supernormal quality of the retinal image. For everyday vision, the penalty of aliasing may be outweighed by the reward of heightened contrast sensitivity and detection acuity.

Huck and Fales's application of communication theory unfortunately relies on the superficial analogy of the eye as an electronic video camera. It ignores much of the neural processing of the image and does not take into account the type of visual task. A rigorous application of this theory would require a deeper understanding of the visual system than we presently have. It is perhaps for these reasons that the approach of Huck and Fales does not predict the enhanced vision already experienced with adaptive optics. Ultimately, the extent to which vision will be improved by correcting ocular aberrations will be determined in the laboratory.

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Moore's Law and the Future of Computing

Joel Birnbaum and R. Stanley Williams of Hewlett-Packard comment on Moore's law (*PHYSICS TODAY*, January, page 38) and discuss the projections of its theoretically anticipated validity until 2012, or even 2020. However, it is more a matter of practicable engineering and technology than it is of theoretical limits of the physical theory.

Interestingly, the researchers of Intel Corp see the whole development rather more pessimistically. For instance, David Papworth, Intel Fellow, suggests that Moore's law won't survive beyond 2004-5. He noted at a VLSi Circuits Symposium in Hawaii in 1998 that by using two or three times as many transistors to increase performance 1.8 times, progress continued apace but at cost: Power consumption has doubled or tripled in each generation. Papworth concluded that, after 2004, density increases will slow down.¹

His colleague Paul Packan, com-