Simulating Vision With and Without Macular Disease

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Conventional photographs do not show how, at any moment of visual fixation, neural vision is clear only in the foveal center. We have developed new computer simulations to show both normal vision and vision with macular disease. These simulations show the nature of momentary vision for life tasks such as reading, facial recognition, and walking in the street. They also dramatically show the impact of macular disease (with scotomas and visual distortion), as there is no surrounding region of clarity. We hope these images will be instructive to both physicians and patients.

A normal view of the world has been simulated for millennia as a clear image over an entire scene: on the sides of caves, in art, and currently in photography and electronic media. Indeed, this is a valid representation insofar as an individual with normal vision can scan the world to examine each detail with clarity, wherever it may be. In this scheme of representation, macular disease is typically simulated as a hazy or gray spot in the center of a picture, and many variations of this approach have been used for physician and patient education.

However, the potential for sharp visual acuity is not constant across the retina. Truly crisp vision is obtained only from central fovea, comprising about 1° of the central field. Thus, at any moment, our view of the world is quite different from a typical photograph. What we actually see during fixation is a small island of clarity amidst a scene that grows progressively more blurry from the center outward. To see images in this form is very instructive for ophthalmologists, both as a means of understanding visual function under different circumstances and educating students and patients about the visual impact of ocular disease. Unfortunately, representations in this manner are not readily available in the clinical ophthalmologic literature.

Many studies have measured visual acuity (and other visual functions) from the fovea outward, using letters and other stimuli. However, only a few images have been published in print or on the Internet to show typical reading matter or scenes that are relevant to patient mobility and there is virtually nothing in the ophthalmologic literature. We have developed sets of photographs that, when viewed in routine fashion, simulate progressive peripheral blurring and that show the effects of a variety of macular disorders. This article is neither a review nor a study of the properties of eccentric vision but an effort to bring this mode of visual simulation to the attention of the field of ophthalmology. We hope that these images will give useful insights about normal and abnormal vision for clinical practice and for patient education.

Our computer software for modifying photographs can be set to simulate general features, such as blur, color, contrast, and brightness, as well as local properties like scotomas, fragmentation, and distortion. Thus, images of this type could also be generated for a wider range of ophthalmic disease.
ECCENTRIC VISUAL ACUITY

Prior studies have measured visual acuity at different retinal eccentricities (eFigure, available at http://www.archophthalmol.com). However, these values do not necessarily represent ordinary vision, since most of the studies used a small number of experienced young observers and sought the best possible resolution. There is no definitive study that documents eccentric vision under less-than-ideal conditions, and no one set of values could be universal anyway, since acuity varies with age, experience, lighting, etc, not to mention ophthalmic disease. Since our purpose is solely illustrative and clinical, we have chosen eccentric visual acuity values that are slightly below those in most of the prior experimental reports (Table).

METHODS

COMPUTER MODELING

The software used for these simulations was custom-designed using Adobe After Effects CS3 (Adobe Systems Incorporated, San Jose, California). After Effects is primarily designed for motion graphics and special effects for movies and video, but it contains an algorithmic expression language that makes it suitable for creating the type of data-driven simulations presented in this article.

The core of the system we developed is a resolution-independent, acuity-based blur algorithm. This allows us to import an image at any resolution (eg, 72 dots per inch for display on a screen, or 300 dots per inch for high-resolution printing) and set parameters that inform the system of the real-world size of the scene represented in the image, the viewing distance, and the view angle. The blur algorithm then calculates the amount of pixel blur needed to simulate a given acuity, taking into account all these parameters, along with calibration data that define the baseline relationship between visual acuity and pixel blur. These data were created by observing different lines of properly sized, randomized Snellen letters in pairs so that one line is slightly smaller than the other. Pixel blur was applied to them until the larger line was just legible and the smaller line was not. Eccentricity fall-off was simulated using this blur algorithm and the values in the Table. However, the system is designed so that it is very easy to switch to other data sets for other purposes. The core project file, along with a sample image and brief instructions, are available on request from the authors.

All aspects of the image—including defect properties such as size, severity, and fragmentation—are controlled by resolution-independent parameters, which can all be adjusted independently of one another. The system automatically adjusts for image size, display resolution, and viewing distance. This gives the system great flexibility to simulate a variety of complex effects, including applying multiple defects to the same image. Finally, because After Effects is designed for motion graphics, the parameters and images can be animated over time to simulate visual scanning on full-motion video.

RESULTS

Figure 1 shows a fundus image with superimposed 5° and 10° eccentricity circles to serve as a point of reference when viewing the photographic simulations. All of the demonstrations have superimposed degree circles as well, so that readers can judge the visual effects with respect to not only visual angle but also the spatial extent of macular disease. We illustrate several different visual tasks that are common in everyday life.

Figure 2 shows 3 views of a page of print, sized so that the image appears true (in terms of visual angle) if the journal is held 36 cm from the eye (a typical reading distance). The first (Figure 2A) is a conventional photograph that illustrates the clarity with which we see the print while scanning the page in a normal fashion. The second (Figure 2B) simulates our view at one moment, looking at the center of the page. We see sharply only in the very center, and even by 2.5° eccentricity, words are becoming difficult to decipher.

One can verify this demonstration with the conventional image, by fixating on one letter in the center while trying to read words just a few degrees off-center. The print still seems crisp but the words are not intelligible. However, the simulated image (and all of those that follow) are intended to be viewed in a normal fashion, ie, scanned as one would look at a conventional photograph. If you fixate on a simulation, then your peripheral blur adds to that of the simulated image.

Table. Values Used for Construction of Simulations

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<thead>
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<th>Eccentricity, Degrees</th>
<th>Visual Acuity</th>
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<td>20/500</td>
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<td>40.0</td>
<td>20/600</td>
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</tbody>
</table>

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The third image (Figure 2C) shows the simulated view with a 2° dense central scotoma. Placing a scotoma in the center of a conventional photograph demonstrates the size of a blind spot but not its full psychological effect because the rest of the photograph is clear. In our simulation, the impact on a patient is much more evident: without central clarity, a patient can barely make out the surrounding fuzzy letters. As noted in the previous paragraph, these simulations are intended to be viewed in a routine fashion by normal-sighted individuals. Patients with macular degeneration will not find these illustrations to be accurate, because their scotomas add to the effects of the simulation.

Figure 3 shows a similar set of images of a group of faces. The visual angle corresponds to a viewer standing 2.7 m from the people in the scene. The first 2 images (Figure 3A and B) show conventional and simulated views, respectively. The last (Figure 3C) shows a 2° scotoma that totally obscures facial details of the central subject. Faces are much larger than print, of course, and we see that patients with a small scotoma will still recognize people fairly well off-center (even if not with total clarity). Note that these images, when viewed from a normal reading distance of 36 cm, span only a bit more than 20° rather than the 40° of the photograph. One can achieve the proper viewing angle by holding the page 23 cm from the eye.

STREET SCENE

Figure 4 also shows a similar set of 3 street-scene images to compare a conventional photograph with the simulated view and with the effect of a 2° scotoma. As with the faces, proper viewing angle can be achieved by holding the page 23 cm from the eye. In this type of environment, a small scotoma prevents reading a small sign or recognizing a face, but has surprisingly little effect on general orientation or cues that would facilitate walking on the street. This helps to understand why...
small scotomas are not a major impediment to general mobility.

**WIDE-ANGLE VIEW**

**Figure 5** shows a wide-angle photograph in conventional and simulated format. This image is far too big (in terms of visual angle) to view comfortably with proper angular dimensions—the eye would need to be 13 cm from the journal page to produce the viewing angles that are shown. Even in reduced format, one can appreciate the complexity of normal vision in resolving such scenes.

**MACULOPATHY**

**Figure 6** shows the page of text (from Figure 2) properly sized for 36-cm viewing, with simulations of a larger zone of maculopathy (extending to 5° eccentricity, typical of age-related macular degeneration or Stargardt disease). Three types of maculopathy are illustrated: a dense scotoma, a fragmented scotoma, and a region of distortion that might occur with epiretinal membrane. The impact of these defects on visual function is much more evident here than with conventional photographs that leave the surrounding text clear, because there is no escape from the devastating effect of the disease. There is a tantalizing halo of low (but usable) vision around the zones of dysfunction, which shows the potential for learning to use eccentric fixation and for adjusting to the location and nature of irregular scotomas.

**Figure 7** and **Figure 8** show the effect of these same types of maculopathy on faces (from Figure 3) and on a street scene (from Figure 4). One can appreciate why orientation and ambulation are relatively unaffected by severe macular disease, even when recognition of faces and street signs straight ahead is largely lost.

**COMMENT**

There is no best representation of vision. Ordinary photography shows a clear world everywhere, which is what we understand as our
Figure 4. Street scene in San Francisco. A, Conventional photograph. B, Simulation with progressive peripheral blur. C, Same simulation as seen with a 2° dense central scotoma. The eccentricities will be correct with the image 23 cm from the eye.

Figure 5. Wide-angle view of San Francisco in a conventional image (A) and with simulated peripheral blur (B). This would need to be viewed 13 cm from the viewer’s eyes to match the eccentricities shown.
eyes scan about. Representations with eccentric blurring (when viewed in a routine scanned fashion) show the properties of our vision as we fixate. The images in this article, with peripheral blurring, illustrate a variety of scenes and visual contexts in a manner that is relevant to practical life and patient education. We believe this representation is more realistic in many ways than conventional photography in emphasizing the dilemma faced by patients who have no alternative once foveal perception is damaged. Even these images may not be entirely realistic, however, because the psychological perception of peripheral vision is somewhat indistinct. We do not necessarily perceive the off-center quality of vision as blurred since the difficulty is less with optical clarity than with altered visual processing (initiated by decreased cone density and increased signal convergence to the ganglion cells).

Some readers may note that artists and others with visual loss and maculopathy have often portrayed their perceptions as either a uniformly blurred image or a blurred spot in the middle of the picture. The painter Edvard Munch drew a black obstruction in the middle of sketches to illustrate his vision around a vitreous hemorrhage. These portrayals are to be expected, given that we routinely photograph or draw the world as it appears through scanning, and in ordinary life we do not stop to think about poor resolution off-center (any more than we think about where our visual field ends). Some perceptive individuals with maculopathy have recognized this issue and given descriptions that echo the effects shown in this article. Georgina Kleege, a novelist and college English instructor with long-standing Stargardt disease, wrote:

Ophthalmology textbooks predict that people with macular degeneration will in fact see a black (or perhaps white) hole in the middle of what they’re looking at. . . . But this is not exactly what I see. . . . Normally, I am more or less unaware of my blind spot. Or else I disregard it. . . . I know that the central area...

Figure 6. Page of print with peripheral blur (from Figure 2) as seen with different types of macular lesions spanning 5° eccentricity. A, Dense scotoma. B, Dense but fragmented (irregular) scotoma. C, Region of irregular distortion (as might occur with epiretinal membrane). The eccentricities are correct when viewed 36 cm from the page.
of my visual field is unreliable, plays tricks, so I focus my attention elsewhere. Of course, peripheral vision is not as accurate or precise as central vision. You cannot read with peripheral vision. Peripheral vision exists to give you a general sense of your surroundings—the forest, not the trees. When I walk, my lack of central vision is less noticeable because it is less necessary. My blind spot precedes me like a giant flying jellyfish. Large objects—fire hydrants, people, cars—fall into it several yards away, then reappear a few feet in front of me.

There is no consensus on the rate at which visual acuity degrades with eccentricity, as noted earlier, and the data will vary with clinical status and the manner of testing. Our purpose with these simulations of vision and disease is not to advocate specific acuity levels or to discuss the psychophysics of eccentric perception, but simply to show how this approach has value for ophthalmology. We have chosen eccentric acuity levels that we think approximate realistic peripheral perception for average subjects under average conditions, and our computer program can be run with alternative values for other applications.

Representations of macular disease raise a number of interesting issues. Our images show directly why reading is severely compromised, while ambulation is not (since most objects in a street scene are still easy to see with moderate eccentric blur). There are some intriguing implications regarding scotoma size. A small scotoma (as in Figure 3) still allows letter recognition comfortably at roughly a 20/50 level, and visual acuity is not reduced towards 20/200 until a scotoma goes well beyond the 5° eccentricity shown in Figure 6. This helps to explain why a small macular hole is tolerated moderately well or why some macular hole operations may seem to help, though an anatomic foveolar defect remains. Conversely, it suggests that when a macular hole reduces vision to 20/200, the problem is much larger than the foveola (perhaps from surrounding edema or local retinal elevation). It shows how the initial effect of a large sco-
toma may be visual acuity of 20/200 or worse, but vision can improve with practice in eccentric fixation at the margin of the scotoma. Our simulations also dramatically show the difficulty of reading with a fragmented scotoma or macular wrinkling, though individual letters can be seen clearly.

In summary, we have presented new simulations of perception during fixation, with or without maculopathy. These images, in which vision falls off with eccentricity, were constructed with a versatile computer program that allows insertion of many different visual and pathologic parameters. We believe that this type of imagery provides new insight into vision and disease and can serve as a model for educational material in many facets of ophthalmology, for both physicians and patients. Finally, the animation capabilities of our program, as that of others,9,10 can simulate active processes such as visual scanning of a page or street scene and add clinical factors such as a scotoma of defined extent or the progression of nuclear cataract over a period of years.

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Online-Only Material: The eFigure is available at http://www.archophthalmol.com.

REFERENCES


Figure 8. Street scene. A, Dense scotoma, producing 20/200 visual acuity. B, Dense but fragmented (irregular) scotoma. C, Region of irregular distortion (as might occur with epiretinal membrane). The eccentricities are correct when viewed 13 cm from the page.
Colorful Visual Experiences During Cataract Surgery

During cataract surgery patients may experience a variety of visual sensations including flashes or colorful shapes. This painting was done by a male, 66-year-old professional artist who had cataract surgery on the left eye. Preoperative examination revealed best-corrected visual acuity of 20/80 OS and refractive error of +1.25 -0.50 × 180°. Anterior segment examination showed 2+ nuclear cataract in the left eye. Phacoemulsification was performed through superior limbal incision with a routine phaco chop technique. A foldable hydrophobic acrylic lens was implanted. The surgery was uneventful and took approximately 25 minutes. The visual sensations described here may be caused by factors such as photoreceptor stimulation by ultrasonic energy or light refraction from operating a microscope within optical interfaces (painting by Carmenzini).

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