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Light Distributions on the Retina: Relevance to Macular Pigment Photoprotection

Richard A. Bone, **Jorge C. Gibert**, and **Anirbaan Mukherjee**
Department of Physics, Florida International University, 11200 SW 8th Street, Miami, FL 33199, USA

Abstract

Light exposure has been implicated in age-related macular degeneration (AMD). This study was designed to measure cumulative light distribution on the retina to determine whether it peaked in the macula. An eye-tracker recorded the subject's field of view and pupil size, and superimposed the gaze position. Fifteen naïve subjects formed a test group; 5 formed a control group. In phase 1, all subjects viewed a sequence of photographic images. In phase 2, the naïve subjects observed a video; in phase 3, they performed computer tasks; in phase 4, the subjects walked around freely. In phase 1, control subjects were instructed to gaze at bright features in the field of view and, in a second test, at dark features. Test group subjects were allowed to gaze freely for all phases. Using the subject's gaze coordinates, we calculated the cumulative light distribution on the retina. As expected for control subjects, cumulative retinal light distributions peaked and dipped in the fovea when they gazed at bright or dark features respectively in the field of view. The light distribution maps obtained from the test group showed a consistent tendency to peak in the macula in phase 3, a variable tendency in phase 4, but little tendency in phases 1 and 2. We conclude that a tendency for light to peak in the macula is a characteristic of some individuals and of certain tasks. In these situations, risk of AMD could be increased but, at the same time, mitigated by the presence of macular carotenoids.

Keywords

retinal illuminance; light damage; macular degeneration; macular pigment

Introduction

Despite a concentration of several defense mechanisms in the center of the retina, it is here that age-related macular degeneration (AMD) wreaks the most damage. The disease is characterized by both genetic and environmental risk factors, underlying many of which is oxidative damage. Because of the presence of photosensitizers in the retina, much of the oxidative damage may be owing to the relatively intense, short-wavelength, focused light to which the retina is subjected. Indeed, long term exposure to ambient light has been associated with an increased risk of AMD in a number of studies. That the damage which AMD inflicts is quite localized raises the question of whether light, integrated over a lifetime, falls uniformly on the retina, or is more concentrated, like the disease, in the macula.

Corresponding author: Richard A. Bone Tel: 1-305-348-3082 Fax: 1-305-348-6700 bone@fiu.edu.
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The purpose of this study was to measure the cumulative distribution of light on the human retina over extended periods of time using eye-tracking technology. Our hypothesis was that, integrated over time, the flux of light falling on the retina is greater in the central macular region than in the surrounding, peripheral region. The hypothesis grew out of a casual observation that bright objects in the visual field tend to grab our visual attention. Confirmation of our hypothesis would provide a model to explain any connection between the incidence of AMD and exposure to excessive ambient light, and why the eye has evolved mechanisms to limit damage by light in the central macula. It would also stress the need for protection of the retina against excessive light and the importance of a diet with sufficient intake of appropriate antioxidants, including the macular xanthophylls, which are implicated in the prevention and retardation of AMD. Currently, nearly 2 million Americans are afflicted with AMD, a number estimated to rise to almost 3 million by the year 2020 (Friedman, *et al.*, 2004). The etiology of AMD is incompletely understood, though both genetic and environmental factors are recognized as role players. Genetic factors include a family history of AMD, race, and the manifestation of AMD in one eye. Smoking is a recognized environmental risk factor, (Eye Disease Case-Control Study Group, 1992) and light is a probable one (Fletcher, *et al.*, 2008). In a relatively recent publication, it was noted that “Long-term exposure to intense illumination may be among the most relevant damaging factors involved in AMD pathogenesis” (Chucair, *et al.*, 2007). About twenty years ago, Young (Young, 1988) wrote that “the retinal damage produced by bright light is most severe in precisely the location which deteriorates most rapidly in age-related macular degeneration.”

Theories on the pathogenesis of AMD focus on the role of oxidative damage to retinal tissue (Beatty, *et al.*, 2000, Mann, 1993, Young, 1988). Antioxidant defenses in some individuals may be weakened as a result of genetics or smoking, and light can induce photooxidation (Schalch, 1992). In the course of their interaction with light, photoreceptor outer segments are continuously damaged. Before they can be regenerated, the damaged portions have to be removed by phagocytosis via the RPE cells and then eliminated through the choroidal circulation. However, because these processes are imperfect, incompletely phagocytosed or eliminated outer segments can accumulate within RPE cells. Such accumulations become visible as drusen and lipofuscin particles, and can result in a diagnosis of early-stage AMD. If the accumulated material overwhelms the RPE cell, it dies leading in turn to photoreceptor degeneration.

Evidence that light may be implicated in AMD is based partly on epidemiology. In one study involving watermen in Chesapeake Bay, ocular exposure to sunlight, in particular a history of exposure to blue light in the preceding 20 years, was deemed a probable risk factor (Taylor, *et al.*, 1992). A similar association between visible light exposure and AMD was reported in the Beaver Dam Eye Study (Cruickshanks, *et al.*, 1993), where sunlight exposure was estimated from the amount of time spent outdoors and the use of sunglasses and hats with brims. For an island population in the Adriatic, 1300 farmers and fisherman had an 18% incidence of AMD compared with 2.5% for town-dwellers who were presumably less exposed to the high levels of solar radiation (Vojniković, *et al.*, 2007). On the other hand, data from three Australian studies have produced mixed results. In a cross-sectional, population-based study, blue iris color (a possible marker of higher retinal light exposure) was significantly associated with increased risk of late AMD (Mitchell, *et al.*, 1998). However, an increased risk of late AMD (but not early age-related maculopathy) was associated with both high and low sun sensitivity of the skin, presumably a marker of the time a person spends exposed to intense sunlight. In a second, case-control study, control subjects had a roughly 20% greater median annual ocular sun exposure than AMD cases (Darzins, *et al.*, 1997). In a third study, the mean annual ocular sun exposure over either a lifetime or the previous 20 years was greater for people with age-related maculopathy than

for those without, but not significantly so (McCarty, *et al.*, 2001). Finally in a French study, in which residential history was used to estimate individual annual sunlight exposure, such exposure was not significantly related to increased risk of AMD (Delcourt, *et al.*, 2001). By contrast, the frequent use of sunglasses was significantly associated with a reduced risk of soft drusen.

Thus the association between AMD and light exposure is not as well established as, say, between AMD and smoking though this is likely owing to the difficulty of quantifying a person's retinal exposure to light and the presence of confounding factors. Adding to the difficulty, either total cumulative exposure to light, possibly over a lifetime, or cumulative exposure to more intense light above some threshold intensity, could conceivably be the more important factor. Here we will describe a feasibility study to explore the use of eye-tracking technology as means of measuring the cumulative distribution of light on the retina.

Materials and Methods

Eye tracking system

The eye tracking system that we used was provided by Arrington Research, and consisted of a lightweight spectacle frame on which were mounted a forward pointing scene camera and a monocular, infra-red-sensitive eye tracking camera and associated infra-red illuminator. The eye tracking camera and associated software were used to determine the gaze position at a frequency of 60 Hz by detection of both the dark pupil and the corneal reflex. Additionally, the height and width (± 0.3 mm) of the pupil were recorded, from which the pupil area was subsequently calculated. The system also provided for automatic blink and saccade detection, and suppression. The scene camera was a color video camera operating at 30 frames per second and set at a resolution of 320 by 240. Its purpose for this study was to act as a semi-quantitative imaging photometer, with the individual pixel values (0 – 255) providing an estimate of the relative light intensity at the corresponding points in the visual field.

A standard calibration of the system was performed for each subject prior to every experiment and between trials. The subject was seated in front of a large projection screen with a head restraint system consisting of forehead and chin supports and a head strap. A computer monitor displayed the live image being captured by the scene camera with an overlaid grid of small, circular calibration targets, one of which (the one to be calibrated) appeared in color. The monitor also displayed the apparent gaze position as another small circle. The operator directed a laser pointer at the projection screen and positioned it so that the monitor image of the laser spot was centered on the colored target. The subject was asked to maintain fixation on the spot on the projection screen while the operator captured the gaze position by depressing the appropriate key on a computer keyboard. This caused the next circular target to appear in color, and the procedure was repeated for a total of 16 targets. The accuracy of the calibration was tested by asking the subject to gaze at the center of the projection screen and then follow the laser spot as it was moved around the screen and noting whether the gaze position was coincident with it. The eye-tracking software permitted “slip correction” if this was not the case.

Subjects

Subjects for the study fell into two categories: naïve and informed. Five informed subjects were familiarized with the study including its goals and hypotheses, and were employed in initial feasibility studies. Fifteen naïve subjects were told only that the study was to determine the distribution of light on the retina. In particular they were never prompted to seek out bright objects in their visual field during the tests. All subjects signed informed

consent forms approved by the University's Institutional Review Board, and the research procedures conformed with the tenets of the Declaration of Helsinki.

Experimental procedures

Experiments conducted with the informed subjects consisted of ~ 10 minute sessions during which the subjects were again seated in front of the projection screen. A Powerpoint presentation, consisting of a sequence of photographic images, was projected on the screen with each image being visible for 3 seconds followed by a 1 second period during which the screen was blank. Subjects were asked to direct their gaze immediately at the brightest part of each photograph when it appeared. In a second series of sessions, they were asked to fixate on the darkest part of each photograph.

The same experiment was conducted with the naïve subjects except that they were given no instructions about where they should direct their gaze; they were simply told to watch the presentation. Additional experiments with these naïve subjects required them to view a short movie sequence on the projection screen, to sit in front of a computer monitor and perform arbitrary computer tasks such as reading their email or surfing the Web, and finally to walk freely around the lab, surrounding hallways and campus. For this latter experiment, which required several slip corrections, the eye-tracker was connected to the computer by a long "umbilical cord," and the computer itself was placed on a small cart which was pushed behind the subjects as they proceeded with their walk.

Data analysis

The recorded data needed for subsequent analysis consisted of the pixel values of each frame in the video captured by the scene camera, the corresponding x and y coordinates of the subject's gaze position, and the corresponding dimensions of the subject's pupil. For this semi-quantitative study, it was assumed that each video frame resulted in an undistorted image on the retina positioned so that the pixel corresponding to the recorded gaze position was centered on the fovea. It was further assumed that the relative illuminance on the retina was the same as the luminance recorded in the video frame. This is a reasonable assumption based upon theoretical analyses of model eyes that showed that, for a uniformly illuminated visual field, the retinal illuminance, at least to an eccentricity of ~ 25° from the fovea, is remarkably uniform (Kooijman, 1983, Pflibsen, *et al.*, 1988). However, our analysis did not take into account the absorption of short-wavelength light by the lens (Van Norren & Vos, 1974) and macular pigment (Bone, *et al.*, 1992), both of which reduce the exposure of vulnerable retinal tissues to photooxidative damage by blue light.

Fig. 1 illustrates the procedure for obtaining the cumulative retinal illuminance (relative) for each recording session. It shows, hypothetically, a stack of four sequential video frames aligned according to the corresponding gaze positions. In a MATLAB program, the pixel coordinates in each frame were transformed with the pixel at the gaze position being assigned the coordinates (0,0). In order to obtain the cumulative retinal illuminance, the program converted each frame from color to grayscale, multiplied every pixel value by a factor representing the area of the pupil, removed the camera's gamma correction, and then performed the addition of resulting pixel values sharing the same pair of coordinates. With reference to Fig. 1, this latter operation would amount to adding vertical columns of pixel values. However, there were two qualifications: If, for a particular frame, the subject's gaze position fell outside the boundary of a central rectangular area having half the dimensions of the frame, that frame was rejected. In addition, only those portions of each frame in the coordinate range −80 to +80 in the x direction and −60 to +60 in the y direction were included in the summation. Without these two conditions, the vertical columns of pixel values (see Fig. 1) could contain varying amounts of missing data.

The result of these operations was a 160 by 120 map with each pixel value representing the cumulative illuminance at the corresponding point on the retina. The dimensions, 160 by 120, were converted to degrees of visual angle, commonly used to specify retinal dimensions, based upon the angular aperture of the scene camera lens. Finally the pixel values in this map were normalized by a scaling factor to a maximum value of 1.0.

Results

The results of the experiments in which informed subjects were asked to fixate on the brightest and darkest objects in a series of photographs consistently verified that the system, procedures and computer analysis were functioning as intended. Fig. 2 is a mesh plot illustrating the light distribution on the retina of a subject who was attempting to fixate on bright objects. The vertical axis represents the cumulative light distribution (relative) on the retina while the horizontal axes indicate displacement from the foveal center in the temporal-nasal and superior-inferior directions. The central peak located at the coordinates (0,0) is a clear indication that the subject was fixating on bright objects in each photograph. Likewise Fig. 3, for a subject asked to fixate on dark objects, is characterized by a pronounced dip in retinal illuminance at the foveal center.

For naïve subjects viewing a Powerpoint presentation of photographic images, there was, in general, no indication that they were spending the majority of the time fixating on the brightest objects. See Fig. 4a, a contour plot of the relative retinal illuminance. For some subjects, there was a small region of increased illuminance at the fovea but the maximum illuminance was elsewhere. See Fig. 4b. For naïve subjects viewing a video presentation, there was a more general tendency for increased illuminance in the center of the retina, but the peak was not necessarily centered at the fovea. See Fig. 4c. The most consistent results were obtained for naïve subjects viewing a computer monitor. In every case, there was pronounced maximum in retinal illuminance at the foveal center. See Fig. 4d. Finally, for naïve subjects for whom data was recorded under free viewing conditions as they walked around the lab, hallways and campus, we had two subjects for whom the highest illuminance occurred at the foveal center. See Figs. 4e and 4f. For others, the contour plots often revealed broad areas of increased illuminance in the center of the retina, but the illuminance maximum was displaced from the center. See Fig. 4g. From the data in Figs. 4d and 4e, we calculated the average illuminance as a function of radial distance from the foveal center. This is shown in Figs. 5a and 5b respectively.

Discussion

The aim of this study was to demonstrate the feasibility of using eye-tracking technology to investigate the distribution of light on the human retina, and thereby help us to gain an understanding of the role of light in the pathogenesis of AMD. Such feasibility was demonstrated at least in a semi-quantitative way. The major problem that we encountered was in the use of the scene camera as an imaging photometer. In reality, the visual scenes that we encounter provide a huge range of luminances spanning at least 6 orders of magnitude. By contrast, the camera had a small dynamic range with only an 8 bit CCD element meaning that it could only record pixel values from 0 to 255. Like other digital cameras, the scene camera had two ways of coping. One, mentioned earlier, was a builtin gamma correction which has the effect of compressing the upper ranges of luminance that are encountered into progressively smaller ranges of pixel values until, above a certain level, all luminances are essentially assigned the same pixel value of 255. For example, when we used a Minolta Spotmeter to measure the luminances of two different objects in a sunlit scene, they were in the ratio of ~ 84:1, yet according to the scene camera, they were in ratio ~ 5.5:1. We attempted to remove this gamma correction in our computer code, but this

would not be accurate for those pixel values at, or close to, 255. The second method of dealing with its limited dynamic range was the camera's built-in electronic aperture. Based upon the overall luminance of the scene, the camera effectively adjusts its gain so that the brightest feature in the scene is assigned a pixel value of 255. Thus the same scene captured on a cloudy day or a sunny day will both result in bitmaps with a maximum of 255. Ideally, the way around these problems would be to replace the scene camera with an imaging photometer. Unfortunately, available instruments are far too heavy and bulky for use on a head-mounted eye tracker.

In practical terms, the spatial variation in cumulative retinal illuminance that we see represented in Figs. 3, 4 and 5 is likely to be greatly under-represented as a result of these transformations imposed by the scene camera. For example, a brief glance at the solar disk lasting only one tenth of a second results in the same cumulative retinal illuminance at the center of the retina as that obtained by staring at a sheet of white paper under room lighting continuously for a day or two. Bearing this in mind, we can still conclude that there are some occupations or activities, such as using a computer, which will result in a peak in cumulative illuminance at the center of the retina for all subjects. Similarly it would appear that there are some individuals whose gaze appears to be drawn more towards bright objects in the visual field than dark objects so that for them the peak in cumulative illuminance is also at the center of the retina. In these cases, increased photooxidative damage in the macula and a higher risk of AMD may be the outcome.

The macular carotenoids located in and around the fovea are, very plausibly, serving the purpose of protecting vulnerable tissues from photooxidative damage both by screening the tissues from excessive blue light and by antioxidative processes such as quenching reactive oxygen species and radicals (Beatty *et al.*, 2000). Barker et al. showed that when monkey retinas were subjected to blue-light-induced damage from 150 μm-diameter exposures, protection by the macular carotenoids was evident in animals with a normal, carotenoid-containing diet (Barker, *et al.*, 2011). Protection was absent in carotenoid-depleted animals, but was restored after carotenoid supplementation. Blue light screening by the macular carotenoids falls to negligible levels within about 5° of the foveal center (Snodderly, *et al.*, 2004), a distance which is certainly less than the half-width of the light distributions shown in Fig. 5. On the other hand, the spatial distribution of macular carotenoids is very similar to that of the cones (more correctly the cone photopigments) (Bone, *et al.*, 2007). From this we might conclude that the macular pigment provides light screening protection specifically for the cones rather than for the central retina generally.

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Abbreviations

AMD	Age-related macular degeneration
CCD	Charge-coupled device
RPE	Retinal pigment epithelium

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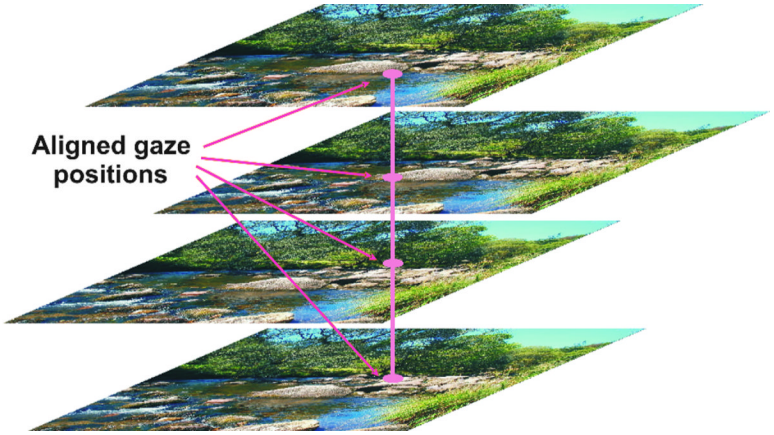

Fig. 1.

Illustration of the procedure for aligning successive video frames captured by the scene camera and imaged on the retina. The images are aligned according to the gaze positions (pink spots). Pixel values lying on the same vertical line, such as the pink line, are added to produce the overall, cumulative light distribution on the retina.

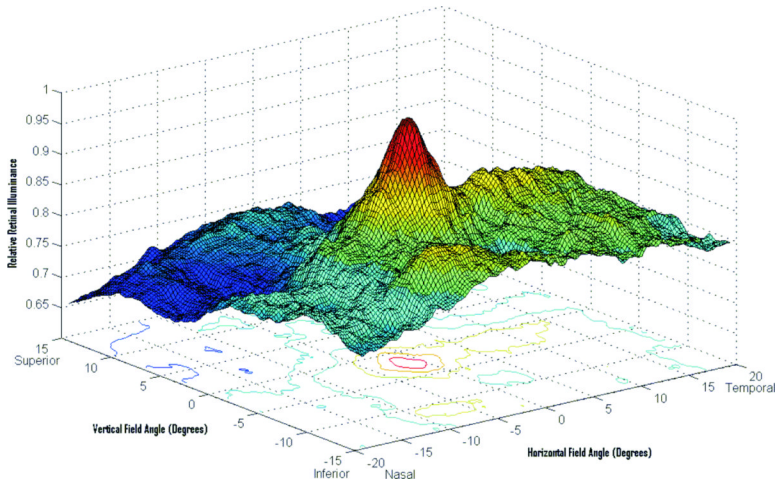

Fig. 2.

Mesh plot showing the cumulative light distribution (relative) on the retina for an informed subject instructed to look at the brightest objects in a sequence of photographic images.

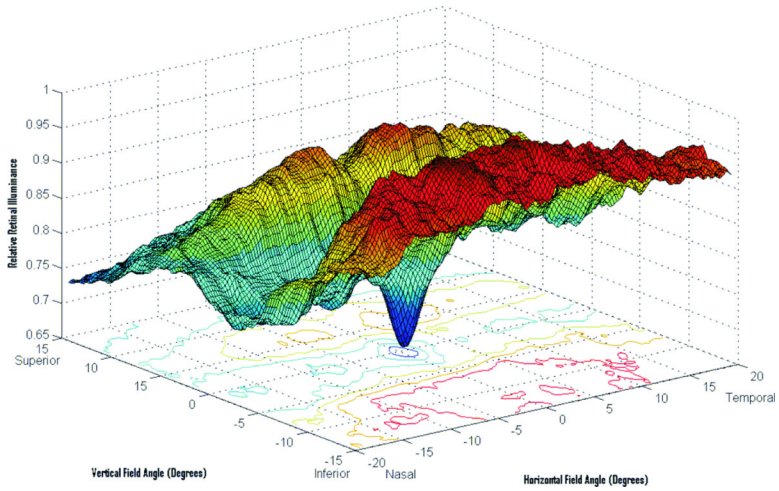

Fig. 3.

Mesh plot showing the cumulative light distribution (relative) on the retina for an informed subject instructed to look at the darkest objects in a sequence of photographic images.

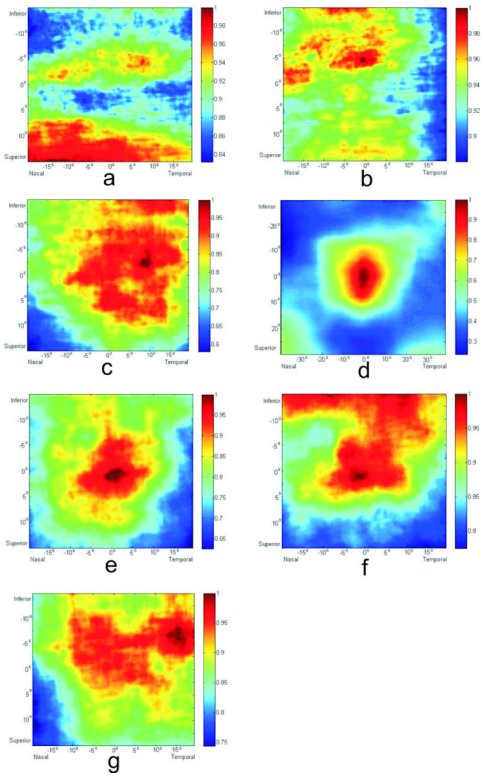

Fig. 4.

Contour plots showing the cumulative light distribution (relative) on the retina for naïve subjects in different viewing situations: a) and b) viewing a sequence of photographic images; c) viewing a video presentation; d) viewing a computer monitor; e), f) and g) free viewing while walking.

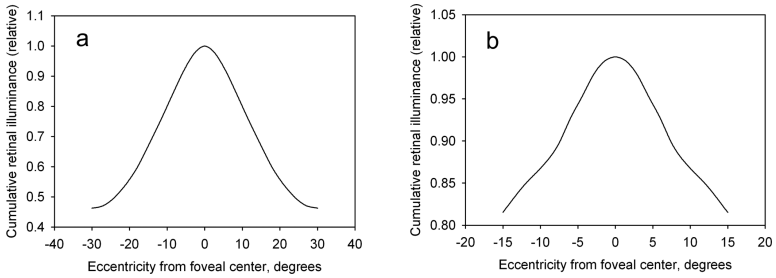

Fig. 5.

Radial plots showing the average cumulative light distribution (relative) as a function of eccentricity from the foveal center: a) derived from Fig. 4d - viewing a computer monitor; b) derived from Fig 4e – free viewing while walking.