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Increases in scattered light causes increased darkness

John J. McCann, McCann Imaging; Arlington, MA 02474, USA

Abstract

What we see is not a simple consequence of the light sent to our eyes. Vision has two powerful spatial transformations of scene luminances: one optical; the other neural. The first spatial redistribution of light is intraocular scatter. Scattered light reduces the dynamic range of the retinal image compared to light from the scene. The second spatial transformation comes from neural processing that causes appearances to vary with the scene's content. A beach scene, (mostly max-luminance scene elements, and maximal scattered light) has the highest slope neural response function. The post-quanta-catch neural mechanisms overcompensate for the intraocular scatter. Low-reflectance objects look darker in scenes with maximal scatter.

Introduction

Vision has two powerful spatial transformations: one optical; the other neural. What we see is not a simple consequence of light sent to our eyes. The first spatial transformation is the redistribution of light by intraocular glare. Every scene elements scatter a small fraction of its luminance onto all other image segments on the retina. The amount of scattered light from each scene element decreases with distance from that scattering element source. The retinal image is the sum of a scene element's luminance and the scattered light from all other scene elements.[1, 2] Scattered light reduces the dynamic range of the retinal image compared with the scene. Nevertheless, the blackest *Black* appearances are found in scenes with maximal retinal glare, such as the appearance of low-reflectance surfaces on a sunny day at the beach.[3, pp. 89-219]

The second spatial processing is neural. *Neural-Response* functions (appearance vs. amount of light on the retina) are variable. Changes in the content of the scene cause changes in the appearance of gray and dark scene segments. A beach scene, (mostly max-luminance scene elements and maximal scattered light) has the highest slope *Neural-Response* function to retinal luminance. The post-quanta catch neural mechanisms overcompensate for the intraocular scatter. In scenes with maximal scatter, low-reflectance objects look darker.

This paper is about *Darkness* in color appearances. The goal is to understand the relationships between the light coming from a scene, light falling on the retina; and the appearance of *Dark* scene segments? This paper is a part of "The Dark Side of Color"; an annual Color Session in IS&T Electronic Imaging meetings discussing topics that deserve more research.

Darkness

In English, the word "*Darkness*" has two dominant definitions: One relates to observations of light and color. The other to emotional feelings of evil, mystery, and a lack of morality. These different definitions have deep emotional roots. Bright light encourages a sense of security about our plans and actions. Darkness encourages a sense of insecurity about what we can see, and what unseen things we should fear.

Humans have a remarkable *Light Detection Range*. When fully dark adapted, we can see a few photons per receptor at absolute light threshold. Snow on a mountain top is about 100 million times more light than absolute threshold. This remarkable range of sensitivities is the result of a mixture of slow (chemical) Dark Adaptation, and fast (neural) Light Adaptation.[4]

Vision improves dramatically with increased luminance. [5] Everything gets better with more illumination: acuity, Ocular Transfer Function (OTF), achromatic scotopic to chromatic photopic, colorfulness, size of color space, and speed of response.

The *Light Detection Range* has little to do with what we are able to see in a particular natural scene. While it describes range, it does not address what we can see in each circumstance. The instantaneous amount of light that comes to our eyes is only one of very many variables that controls vision. This paper discusses how many of vision's mechanisms interact to control what we see in different circumstances. We use vision to monitor the world at an instant, in a place, at a time. While the amount of light from snow in the Alps is interesting, it is not relevant to seeing, unless you are there.

Seeing

Figure 1 diagrams a cascade of 8 general steps in "Seeing: Photons to Appearance". Each of these steps is a well studied topic in physics, optics, psychophysics, neurophysiology, and painting. Each step has an important role in understanding *Darkness*. Figure 1 is a roadmap for the following discussion.

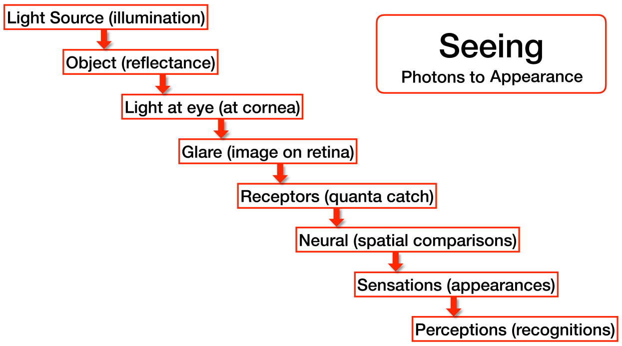

Figure 1. An 8 step cascade of steps in "Seeing: Photons to Appearance".

In step 1-3 light falls on an object that reflects a fraction of it to the eye. Alternatively, light travels from sources (displays) directly to the observer's eye.

Step 4 *Glare* is the first spatial transformation, namely altering the spatial distribution of the scene's light. Step 4 is the convolution of all the scene's luminances with the eye's Glare Spread Function (GSF). This convolution calculates retinal luminances from scene luminances for the entire scene. It substantially changes the luminance values for the darkest scene segments in all real-life High Dynamic Range (HDR) scenes. By scattering light, it degrades the image of the scene, and reduces the range of light falling on the retina.

Step 5 uses spectral sensitivity functions to calculate the quanta catch of receptors. Retinal receptor's outer segments are the location of photopigment that bleaches, and regenerates in the dark. This balance of bleached and unbleached photopigment controls the 100 million : 1 changes in sensitivity to light. However, it does not control the detailed appearances of scene segments at a particular light level.

Receptor response output is the input to neural spatial image processing; in the retina, along the visual pathway, and in the cortex. Every step along the visual neural pathway integrates and compares spatial information from the retina.[5] Step 6 *Neural* is the second spatial transformation, namely, it introduces variable neural responses to fixed receptor quanta catch. The interesting fact is that glare's spatial transformation degrades the contrast of the retinal image. Then, *Neural spatial comparisons* compensate for glare.

Psychophysics provides experimental measures of what we see. Here in Step 7, we use the term *Sensation* to describe observer measurements such as matches, or Magnitude Estimates (MagEst) of what we see. These matches and estimates quantify appearances. These matching and estimating procedures provide a bottom-up description of appearance.

Step 8's *Perception* [6,7] is a top-down approach to associate objects by inference from light-responses of earlier steps.

Appearance of white

The appearance of scene maxima is easy to explain. The scene element with the highest luminance appears *White*. The higher its luminance, the brighter *White* looks. Glare has minimal effects on the retinal image of *Whites*, while it can alter substantially the retinal image of *Dark* segments.

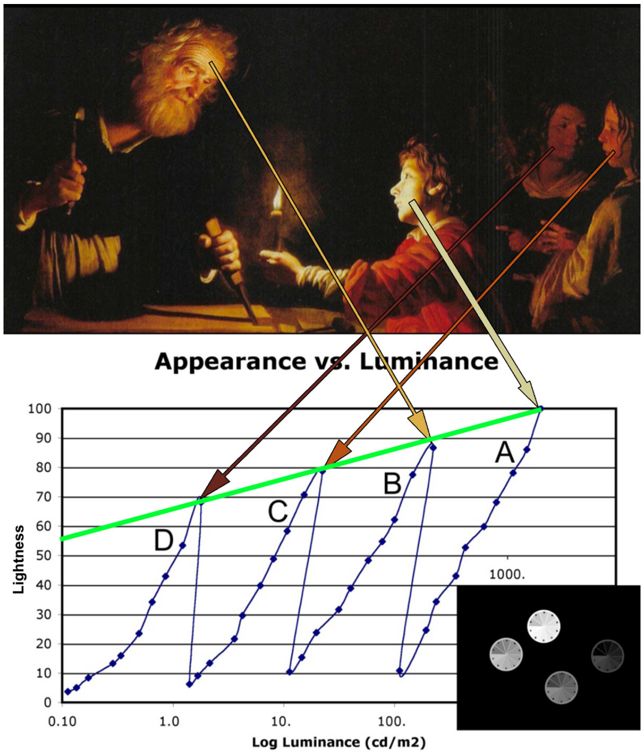

Figure 2. (bottom right) Illustration of the HDR lightbox display with transparent film circles on an opaque background. The display's range is 18,619 : 1. (bottom graph) Plot of the appearance (Lightness) of each pie-shaped segment as a function of that segment's luminance (blue line). A (top) is a plot of the circle with the most light. B (left), C (bottom), and D right have 1.0, 2.0, and 3.0 log units less light. The Green line plots the appearance of the local maximum luminance in each circle.
Figure 2 (top) is van Honthorst's 1620 HDR painting (Hermitage). Arrows connect painter's image segments with MagEst data.

Figure 2 has four circles, each with 10 pie-shaped image segments on an opaque background (shown in the bottom right). This entire HDR target has a 4.3 log unit range of luminances. Each of the four circles has 10 luminance segments. Each with a different range of luminances. In the graph (bottom), the blue line plots appearance (Magnitude Estimate of Lightness) versus log luminance for all four circles. Observers were instructed to assign 100 to the whitest *White* and 1 to the blackest *Black*. Circle A has the maximum luminance in the display; that pie-segment appears lightness MagEst=100. Circle A's darkest segment (luminance 5%) has lightness 11. Most of the white/black appearance range is generated by 20:1 range in luminance.

Circle B's maximum luminance appears only slightly darker (MagEst=89) than the maximum luminance in A, despite its much lower luminance. The maximum luminance in Circles C and D show the same slightly darker trend in appearance (MagEst C=80, D=70). The green line plots the appearances of the local maxima as a function of the segment's luminance.

Local maxima fit a simple function of scene luminance. The surprising observation is that *Whites* have a constant response for most, if not all, scenes and experimental displays. However, not all appearances in the scene are constant. Grays and blacks vary with the content of the scene. Local maxima are different. Regardless of the scene's content, the appearance of local maxima fit the same low slope function of luminance plotted by the green line. Some examples of different scenes are:

- **Stellar Magnitude** - In 200 BC, Hipparchus of Nicea quantized appearances of stars into 6 brightness magnitudes. This began two scientific studies: One measures the light coming from celestial bodies; The other measures the eye's light-response function. Ptolomy described and expanded Hipparchus's observations. In 1856, Pogson made Stellar Magnitude a photometric measurement. Stellar magnitude changes by 100:1 when the measured luminance changes by 100,000:1.[8, 9]
- **Measurements of brightness** - Many experiments report the same plots of maximum brightness vs. luminance.[10] Bodmann et al,'s used magnitude estimation experiments to measure brightness.[11] Bodmann's data fits Stellar Magnitude, and the green line plot in Figure 2.
- **Practice of HDR painters** - Figure 2 (top) shows van Honthorst's 1620 HDR painting "The Childhood of Christ". It shows a dramatic HDR scene illuminated by a single candle. It is rendered very successfully in the 30:1 range of oil paints. The highest reflectance paint renders Christ's face, analogous to the maximum luminance in circle A. The other faces are analogous to the local maxima in B, C, and D. Painters for centuries have used local maxima in rendering HDR scenes. Figure 2 simply quantifies their practice.
- **Measurements of Appearance in HDR scenes** - There are many other examples of vision's unique response to local maxima (The Hipparchus Line). [3 pp.180-380, 12, 13]

It is interesting to note that *Whites* are unique appearances, in that they are the only apparent color that correlates with receptor quanta catch. White appearances do what photographic films and electronic light sensors do. Whites correlate with photon counts. Unlike camera films and sensors, whites change their brightness and chromatic appearance very slowly with quanta catch.

- *Whites* have a single light/appearance (input/output) function regardless of the scene's content.
- Whites measure the same light-response functions in both *aperture* and *object* mode[6] test targets.

Appearance of Darks

The appearances of scene segments at the dark end of the range is much more complicated. The appearance of *Dark* segments depends on the scene luminance, the light reaching the eye after intaocular glare, the receptor quanta catch, and the spatial image processing by post-receptor neurons. *Dark* segment luminances are substantially altered by glare and neural processing. *Dark* segments show extensive changes of their light-response functions in steps 4 through 6. This cascade of signal processing leads to darker scene segments, even though glare adds light to it. Adding light to other parts of the scene can decrease the visibility of what you are looking at. *Dark* scene segments can act in counter-intuitive ways.

Appearance of less than Maxima

The appearance of the *Dark* scene segments is much more complicated than *Whites*. This complexity begins back at Step 4 with Intraocular *Glare*. While maximal luminances are minimally changed by glare, lowest scene luminances are radically changed. Both human retina and camera images show these dramatic changes, even though the underlying mechanisms are different.

Camera Glare

Figure 3(left) is a photograph of the actual lightbox HDR scene when circles A, B and C are covered with an opaque sheet. Only the circle with the lowest luminance is visible in the darkroom. The very long camera exposure of 16 seconds made the best photograph of this dimmest scene circle.

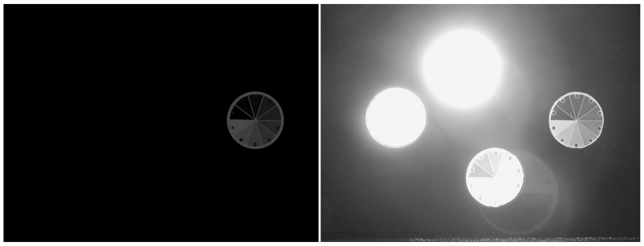

Figure 3(left). Photograph of lowest luminance circle D shown in Figure 1. Circles A, B, and C were covered with an opaque sheet.
Figure3 (right) Photograph after the opaque sheet was removed. All camera settings were identical. Glare from circles A, B, and C caused all the changes in camera response. Both photographs were taken with Nikon Coolpix 990.

In Figure3(right) Circle A has 1000 times more luminance than circle D. Although circles A, B, and C circles are at a distance, they contributed enough stray light to change the camera's response to circle D. The added light caused:

- All pie segments in Circle D had elevated digital values.
- All of circle A and B, and most of C saturated the camera sensor at its maximum value.
- The stray light increased the size of circle B somewhat, and considerably increased the size of circle A.
- The stray light caused an out of focus fog in the center of the display. All background digits are nonuniformly higher.
- Several surface reflections created sharper magnified parasitic images.[3, pp. 91-121]

Both human retina and camera images show these dramatic changes, even though the underlying causes are different. Parasitic images result from multiple air/glass surface reflections, and are not found in intraocular glare. Further, human intraocular glare results from Tyndall scattering and reflections from the fundus. Nevertheless, the above photographs, made for measuring the HDR limits of cameras provides a dramatic illustration of glare's effect on images of HDR scenes. [3, pp 91-121]

Human Glare Spread Function

In order to understand glare on the retina we need to convolve the eye's Glare Spread Function (GSF)[1] with measurements of light from scenes. We used a MatLab program[2] that implements Vos and van den Berg's measurements of human GSF.

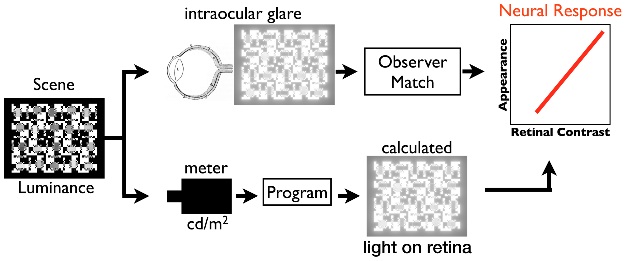

Figure 4. Illustration of the technique that compares retinal stimulus with psychophysical appearance. First, calculate the light on the retina. The array of accurate scene luminances (meter readings) is the input to a program that calculates retinal contrast (horizontal axis). Second, observers measure appearances. Observers made Magnitude Estimates of appearance of image segments (vertical axis). Neural Response function (plotted in red) describes post- quanta-catch spatial image processing of a scene.

Figure 4 illustrates the conversion of scene luminance to relative Retinal Contrast. We can isolate the properties of neural spatial processing from optical veiling glare with the plots of *Neural Response* functions for different scenes. More important, we can measure the effects of the rest of the scene on appearance.

The program[2] calculated the image on the retina of the three HDR scenes illustrated in Figure 5.

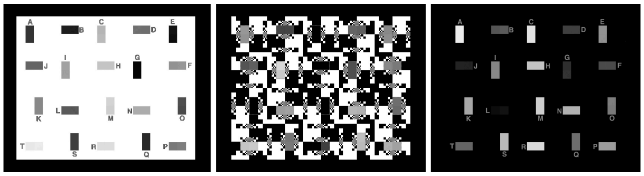

Figure 5. Illustration of 3 HDR displays. (left: Maximum glare)Twenty pairs of square test segments surrounded by maximum luminance. (middle: Average Glare) Twenty segments surrounded by half-max/half-min luminances. (right: Minimum Glare) Twenty segments surrounded by minimum luminance.

All three HDR scenes have a range of >5 log luminance units. Observers were asked to identify the image segment that had the highest lightness (whitest *White*), and write the Magnitude Estimate =100 on an outline map of the image. Then, they selected and mapped the image segment that appeared the blackest *Black* (MagEst=1). Mid-gray identification and mapping bisected White/Black. The process continued until all 20 pairs of square segments were assigned Lightness values for all three targets in Figure 5.[3 pp. 123-171]

During the experiment observers were asked if the appearances of each "*White*=100", in each of the three surrounds, appeared the same *White*. Observers reported "*Whites=100*" looked the same in all targets. The darkest appearances in the scenes, "*Black*=1" were also reported to be same appearances in all targets. The three HDR scenes had the same range of *White/ Black* appearances.

Figure 6 shows that optical veiling glare from all three backgrounds reduces the more than 5 log luminance scene range.

With Minimal glare, the range on the retina asymptotes at just below 4.0 log units. With a surround that is half/Max and half/Min, the range of the retinal image is less than 2.0 log units. With a Maximal glare surround, the range of the retinal image is less than 1.5 log units. The Maximal Glare surround has changed the scene's range from ~1 million:1 down to 30:1. (30:1 is the range of white to black papers in uniform illumination.) [3, pp. 123-171]

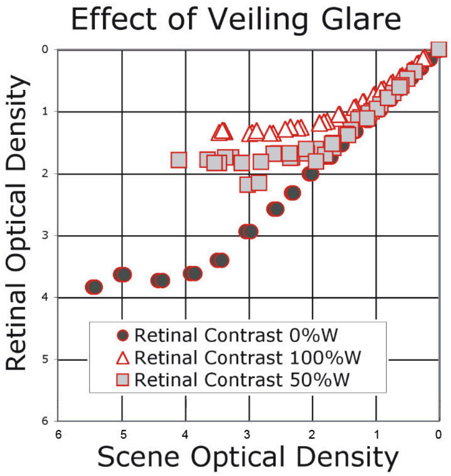

Figure 6. The three plots of light on the retina for scenes with Maximal (100%W), Average (50%W), and Minimal (0%W) glare from different surrounds. Scene Optical Density is the logarithmic plot of the relative luminances of HDR scene segments. Retinal Optical Density is the logarithmic plot of their retinal image values.

Neural-Response Function

Figure 7 shows three very different *Neural-Response* functions. The horizontal axis is the amount of light on the retina from Figure 6. The vertical axis is the White to Black appearance from MagEst data. The maximal retinal stimulus (Log=0) appeared the same *White*=100. The appearance *Black*=1, however, had retinal stimuli that were 1.5, 2.0 and 4.0 log units less light. These light-response functions define the ranges of white to black as : 30:1 in Max luminance scene; 100:1 in average scene; and 10,000:1 in Min luminance scene. An object that looks black on the beach has one part in 30 of the light on the retina, while in stars at night black on the retina has to be 1 part in 10,000. [3, pp. 123-171]

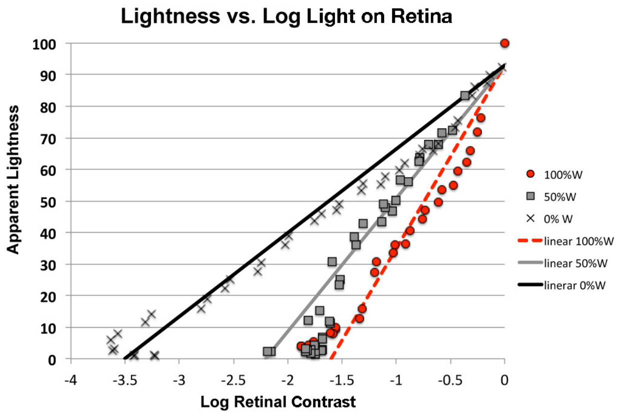

Figure 7. Plots of apparent lightness sensations as a function of log amount of light on the retina. The Appearance White =100; Mid gray =50; Black =1.

Lightness Response Function

Lightness is the visual appearance between white and black. Both psychophysics and neurophysiology experiments have measured the shape of this light-response function. The problem is that neurophysiology reports a logarithmic response, while psychophysics reports a cube-root function.

In physiology, the magnitude of change in photocurrent from rods and cones is proportional to the logarithm of their quanta catch[5 pp. 573]. Many measurements agree that receptors have a logarithmic response to light. [14,15]

In psychophysics, Munsell measured equally-spaced steps in Lightness using appearance bisection. Wyszecki [10] described a number of light-response functions. CIE (1976) established L*, namely, it standardized Lightness as a cube-root function of scene luminance. Stiehl, et al. [16] bisected an HDR transparent display to measure equal increments of HDR appearance. Their data found a cube-roof function of scene luminance.

Stiehl et al. [16] also calculated the amount of light on the retina for their equal lightness steps. Lightness is a logarithmic function of retinal luminance. The conflict of logarithmic vs. cube-root Light-Response Functions is resolved by recognizing the role of intraocular glare. Receptors respond to the convolution of scene luminances with intraocular glare's GSF. CIE L* Lightness's cube-root function is an artifact of intraocular glare.

Cataract's influence on Black

Figure 6 shows that glare has a very large influence on the retinal stimulus in real HDR scenes. If glare is so large, why don't we see it in everyday life? Even patients with operable cataracts, that distort scene luminances, do not observe the effect of glare in daylight conditions. Special circumstances are needed to see the effects of cataracts. The new moon, a sliver of very bright light on a dark sky is an ideal cataract target. Multiple images and distortions of the moon are easily seen. In night driving, the instantaneous loss of vision from headlight glare is apparent. However, in daylight situations we found very few observable effects of cataracts.

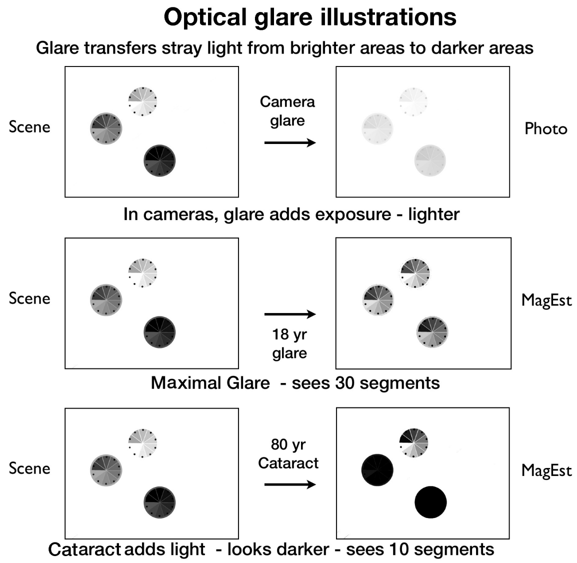

Figure 8. Illustrations of the effects of glare in: cameras, normal vision, and cataracts. (top) Camera optics adds light raising the cameras responses. (middle) An 18 year old observer with normal vision identifies 30 different scene segments. An eighty year old observer with cataracts can only distinguish 10 segments. 20 segments appear black.

Figure 8 illustrates the different effects of glare in camera photographs, and visual appearances. In all cases glare from uniform maximum glare adds light to the lowest luminance scene segments. Lowest luminances have the most change from glare.

Figure 8 illustrates experimental results of additional measurements using the lightbox display in Figure 2. For these experiments the opaque mask and circle D were removed. Figure 8 uses the maximal glare surrounds to compare the response of cameras, and two observers. The first is an 18 year old male with normal vision. The second is an 80 year old female just before cataract surgery..

Cataracts are an excellent illustration of how adding light to low-retinal-luminance image segments makes them appear darker. Why? Ordinarily, more light appears lighter. The purely optical effect can be measured by changing the lightbox's background from opaque to transparent. Figure 8 top illustrates that glare increases camera responses.

Figure 8 middle illustrates MagEst data of a young normal eye. He can differentiate all 30 pie segments. The 80 year old with PreOp cataracts can differentiate only 10 gray pie segments. The other 20 appear black. Her glare reduces the contrast of edges in her retinal image. That combined with the increased slope of her maximum glare *Neural Response* function (Figure 7) makes 20 pie segments appear black. The maximum-luminance background increases the slope of that scene's *Neural Response* function. Higher neural slope means darker appearances. Higher neural slopes also explains the lack of visibility with glare. Higher slopes hide glare. They counteract the degradation of the retinal image by intraocular glare. Higher slopes with high luminance surrounds increase apparent constancy.

The 80 year old observer had performed the same experiment 12 years earlier. At the age of 68, she could discriminate 26 steps. After cataract surgery her discrimination improved from 10 to 20 pie segments.

The combination of the effects of glare in Figure 6, with the change in slope from background in Figure 7 takes us to Figure 9. Neural slope counteracts glare and improves apparent constancy.

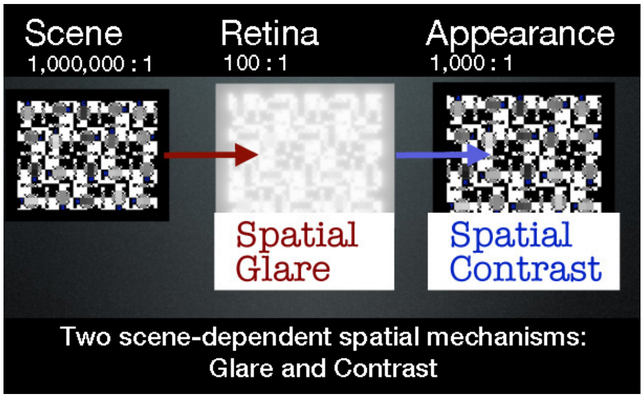

Figure 9. Illustration of vision's two competing spatial-processes: The effects of Glare, and the effects of neural spatial processing. While a scene has nearly 1 million to 1 range of light, the retinal image is reduce to 100:1 by glare. Scene-dependent neural processing counteracts glare.

Discussion

The appearance of *White* is easy to describe. A very-high-luminance scene maximum appears the "whitest *White"* sensation. That *White's* appearance tracks astronomers' Stellar Magnitude function first documented by Hipparchus in the 2nd century BC. *Whites* appear slightly less white with decrease in luminance. Nevertheless, the maximum luminance in all scenes appears one of many *Whites*. Local maxima, with slightly lower luminances, in the same scene also appear very slightly less white. *Whites* are a slowly changing response to receptor quanta catch (absolute luminance).

Dark scene segments are much more complicated. The appearance of the darkest scene segments is controlled by two powerful visual spatial processes. The first is intraocular glare, namely the convolution of all scene luminances with the eye's GSF. That spatial transformation adds light to the retinal image of lower luminance scene segments. The amount of light added depends on the luminances and distances of all the other scene segments.

Darkest apparent objects on a sunny day at the beach are the result of high-glare (reduced range) and high-slope glare compensation. At night, darkest objects are the result of less light (increased range) and a lower-slope neural processing.

When a glare source is suddenly introduced to a scene, intraocular glare reduces the spatial ratios of retinal luminances, compared to scene ratios. However, that sudden addition of a glare source also changes the slope of the *Neural Response* function. That higher slope amplifies the smaller luminance ratios. The combined effect of intraocular glare and neural processing tend to cancel. Appearances tend towards constancy by reducing the effects of glare.

More research is needed to quantify the properties of Intraocular Glare Constancy. In particular, this research is needed for understanding night driving conditions. The onset of headlights changes the slope of neural processing, so that dim objects appear darker. Detecting dim objects is essential for night driving. The experiments described above study the lightness of dim objects in HDR scenes. They do not study changes in detectability by isolating the optical and neural components of seeing.

Summary

Whites, the appearance of local maxima, correlate with both scene luminance and receptor quanta catch. Appearance fits a single low-slope function of luminance.

Darks, the appearance of minima, do not correlate with either scene luminance, or receptor quanta catch. Appearance has to be modeled by two sequential spatial transformations: a convolution of scene luminance with the human GSF; and a variable neural spatial process that responds to the content of the scene. This second neural response is a high-slope counter measure to glare's lower contrast retinal image. Glare is a convolution of scene luminance. Neural response is result of spatial comparisons of retinal luminance. Modeling Glare Constancy requires luminances from the entire field of view; but one input is scene luminance, the other is retinal luminance.

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Author Biography

John McCann received a B.A. degree in Biology from Harvard College in 1964. He worked in, and later managed, the Vision Research Laboratory at Polaroid from 1961 to 1996. He currently consults and continues to do research on color. He has studied human color vision, digital image processing, large format instant photography and the reproduction of fine art. His 140 publications have studied Retinex theory, color from rod/Lcone interactions at low light levels, appearance and intraocular scatter, and HDR imaging. He is a Fellow of the Society of Imaging Science and Technology (IS&T) and the Optical Society of America (OSA). He received the SID Certificate of Commendation. He is the IS&T/OSA 2002 Edwin H. Land Medalist, and IS&T 2005 Honorary Member. He is past President of IS&T and the Artists Foundation, Boston. He served as Secretary of the Inter-Society Color Council, the USA Member body of AIC. He has spoken at Electronic Imaging meetings since 1988.