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Pseudocolor Analysis of Glare's Paradox in Illusions

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Abstract

Glare introduces a complex scene-depended transformation of the array of "All Scene Luminances" making a different spatial pattern in the array of light on all receptors, called "Retinal Contrast". The spatial convolution of "All Scene Luminances" with Vos and van den Berg's CIE 1999 Glare Spread Function calculates high-resolution arrays of "Retinal Contrasts". The results show that uniform-luminance scene segments become low-slope gradients that are nearly invisible, or invisible. Visual inspection of these arrays is misleading. Plots of calculated "Retinal Contrast" values, histograms, and other numerical techniques are needed to analyze the effects of glare. Pseudocolor Look-up Tables (LUT)s are very helpful in visualizing the complexity of glare's spatial transformation that controls the amount of light falling on rods and cones.

This article studies Lightness Illusions that contain two identical scene-luminance segments that are identified as the "Regions-Of-Interest"(ROI). Following receptor responses, neural spatial processes generate a second spatial-image transformation that leads to appearances. Contrast, Assimilation, and Natural Scene Illusions demonstrate [Appearance ≠ scene luminance]. Analysis of Illusion's patterns of light on receptors shows that: Contrast Illusions, Edwin Land's B&W Mondrian, Adelson's Checkershadow all exhibit Glare's Paradox. Namely, that vision's second neural transformation overcompensates the effects of glare. Illusions' GrayROIs appear darker despite large amounts of glare light on receptors. GrayROIs that appear lighter have smaller amounts of glare. Assimilation Illusions adds light to GrayROI's that appear lighter. The combination of intraocular glare and Lightness Illusions shows complex-spatial-image-processing transformations following receptor responses in normal scenes.

Introduction

Studies of human vision require measurements of light from the scene. This data includes the luminance, and the angular subtend of each scene element. High-Dynamic Range (HDR) scenes introduce very large amounts of intraocular veiling glare. Glare introduces a complex optical spatial transformation of scene luminances. The quanta catch of receptors is the sum of scene luminances plus glare's light re-distribution from the scene [1].

This article studies how glare affects normal-dynamic-range Lightness Illusions for two reasons. First, Lightness Illusions demonstrate vision's spatial image processing. Second, Illusions work well in the limited range of light found in printed books, and Low-Dynamic-Range scenes.

Lightness Illusions contain two identical "Gray" scene-luminance segments that are identified as the "Regions-Of-Interest" (ROI). Those segments appear the same if "the rest-of-the-scene" is restricted to a single uniform luminance. However, the designers of Lightness Illusions introduce clever "rest-of-the-scenes" that makes identical GrayROI luminances have different appearances. Since glare re-distributes light from all of the scene's pixels, the question becomes does the Illusion's "rest-of-the-scene" alter those equal scene luminances to make unequal retinal receptor responses.

Contrast and Assimilation targets are the combination of low-dynamic-range scenes (smaller glare magnitudes), and extreme "rest-of-the-scene". The million-to-one HDR input range is reduced to 200:1 for Lightness Illusions on our experimental display. However, Contrast and Assimilation "rest-of-the-scene" uses only max- and min-luminance segments. This combination has a normal range of glare, but has dramatic local spatial glare caused by the exclusive use of max-and min-luminances in "rest-of-the-scene".

Glare has its strongest effects on the darkest scene segments, moderate effects on mid-range segments; and minimal effect on the brightest regions. However, glare's most influential effects are found at edges between different scene segments, and changes in uniformity. Glare transforms the scenes' sharp edges into high-slope gradients; and transforms uniform scene luminances into low-slope gradients, that are hard to see.

Retinal Contrast

Luminance, unambiguously defined in physics, is the input to vision; namely, the calibrated light from a specific scene segment that reaches the eye's front surface. The light that reaches the rod- and cone-receptors is transformed by glare into a different spatial pattern. In most Natural Scenes we seldom observe the effects of glare. Usually, we make assumptions that glare is too small, or below some threshold to influence appearances in Natural Scenes. Recent HDR studies have shown that glare sets the variable scene-dependent range of light falling on receptors. These experiments measured scenes with ~1.0 million:1.0 scene range [log_range=5.4]. The retinal range is [log_range=1.5] on receptors.[2,11] Those programs convolved the calibrated <*scene_luminance*> input array with 1999 CIE Glare Spread Function (GSF) by Vos and van den Berg [3]. The retinal image is the sum of scene luminance, plus light scattered into each pixel. The amount scattered into each pixel is the sum of the veiling glare from all other pixels. Each glare contribution depends on the luminance of the donor pixel and its angular separation between the donor and receiving pixels. The CIE GSF is plotted on log-log axes. The horizontal axis covers (1 minute to 60°). The vertical axis plots the decrease in glare as a function of the angular separation covering 8 $\log_{10}$ units (150,000 to 0.005). Despite its extremely large ranges, it does not approach a constant asymptote.[3]

The name "*Retinal Contrast*" is the program's output image. The GSF convolution conserves the total energy in the input *scene_luminance* array. It redistributes all of the input energy into the output image. As described by Hecht et al.[4], the light falling on receptors is attenuated by front surface reflection, intraocular and macular pigment absorptions. The eyes' pupil size, and pre-retinal light absorptions are not accounted for in the program. The term "*Retinal Contrast*" is the output of our Matlab [2] and our new, more accessible, Python code [11]. It is the normalized, linear photopic energy/pixel in a flat array congruent with the flat visual test targets. The program does not use the term retinal luminance because the calculation does not measure intraocular light attenuation. "*Retinal Contrast*" is the ¿term for term is the model's output: normalized, pattern of light on receptors.

In today's world, most visual media are seen on electronic displays. Their ~10% surface reflectance becomes black in displayed images. Digital displays of illusion have replaced those on printed pages. Investigating appearances in Natural Scenes have become the high-resolution study of edges and gradients of light, replacing the study of printed reflectances and illuminations. It is difficult to discuss Illusions on a screen in terms of its reflectance and its illumination. The monitor's reflectance (physics) is irrelevant background light, because the image is all emitted light. Displays are illumination with edges and gradients. The thoughtful explanation of Illusions has moved on to the analysis of spatial patterns of light. The analysis of reflectance and illuminance becomes a historical footnote, while the "Scene Luminance" spatial array is the source of information that generates the appearances.

Display, Calculations and Analysis Tools

Fig.1 is the Flowchart of analysis of Illusion's pattern of light on receptors. Each Illusion uses 8 different digital <*image*> files.

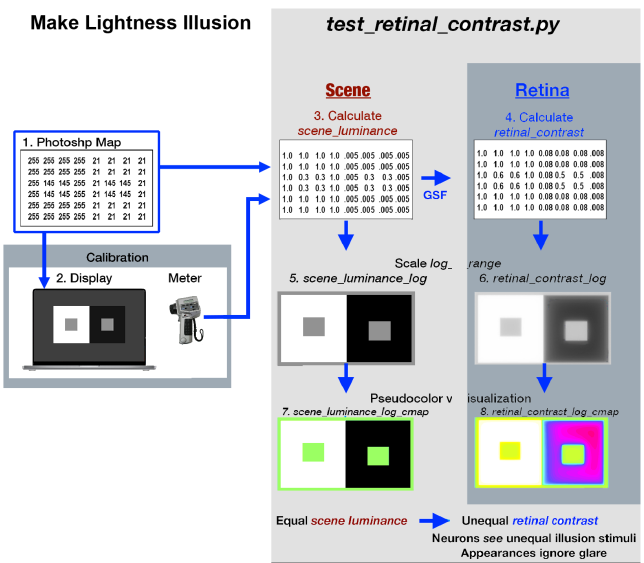

Fig. 1 Flowchart of making digital files, displayed on a computer screen, then measuring calibrated scene_luminances, then calculating 64-bit linear arrays of scene_luminance and retinal_contrast (top-row). Both arrays are analyzed using numerical techniques (middle-row), and pseudocolor visualizations (bottom-row).

In Figure 1, we made an Illusion on the computer display using an 8-bit integer <*file*> of all pixel values at each [x,y] location Calculations of light patterns on receptors require specific information about both input luminances and visual angles. The <*scene_luminance*> input requires high-resolution, linear, calibrated data expected by the CIE 1999 GSF. As well, <*pixel_size*>, and <*viewing_distance*> are required to specify each pixel's visual angle. The <*age*> and <*iris_color*> are required to identify the level of observers' intraocular glare. Our study used [*age*=25]; [*iris_color*= brown]; for observers with minimal glare.[3]

The program that calculates <*retinal_contrast*>, first makes a [2048,2048] pixel, 64-bit, normalized, cd/m² file, called <*scene_luminance*>. The file <*retinal_contrast*> is the padded FFT convolution of <*scene_luminance*> with CIE1999 GSF.[3] The <*retinal_contrast*> output is the linear normalized light pattern on retinal receptors. Each Illusion has 8 digital files in this process.[11]

Analyzing the Retinal Image

The analysis of <*retinal-contrast*> uses quantitative plots of numerical values from both scenes, and contrast calculations. These image files cannot be displayed at full range, and full resolution on monitors. As well, vision's spatial-image processing suppresses the visibility of luminance gradients[5]. Visual inspection of <*retinal_contrast*> files makes two flawed assumptions. First, it ignores our vision's spatial suppression of gradients. Second, it ignores the fact that looking at the calculated image adds a second pattern of actual optical veiling glare to the monitor-displayed calculated glare image. Visual inspection is quantitatively inaccurate. Numerical analysis, and pseudocolor renderings are needed to fully appreciate <*retinal_contrast*>*:*

- GSF transformed all discontinuous sharp edges into retinal gradients.
- Many low-slope gradients are below human detection threshold. Visual inspection does not 'see" gradients of light.
- Pseudocolor maps, with visible quantization steps, converts subtle luminance gradients into discriminable bands of color, allowing readers to visualize bands of equal-luminance regions, that reveal glare's non-uniform luminance transformations.

Appearances are the consequence of glare plus neural processing. Glare is a simple optical process (rapid decrease in scatter with increase in visual angle).[3] The GSF is convolved with all <*scene_luminances*>. The entire content of the scene is the co-creator of the pattern of receptor responses.

Pseudocolor Look-Up Tables (LUT)

Fig. 2 illustrates the log input and output files using two different LUT visualizations.

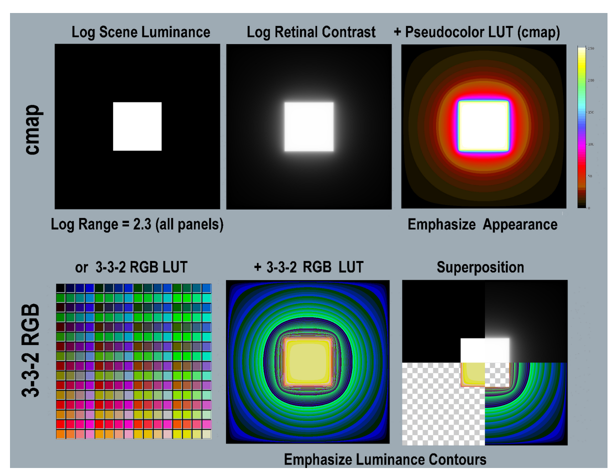

Fig. 2 *Illustration of Pseudocolor Look Up Tables (LUT). File [cmap.LUT] (top-row) emphasizes the order of lightness appearances. ImageJ®'s File [3-3-2 RGB](bottom-row) emphasizes bands of uniform luminances by introducing contours. Both pseudocolor LUTS were rendered in Photoshop using the [wide gamut RGB] profile.*

The top-left panel in Fig. 2 shows a 2049 by 2049 pixel background(min-luminance) with a 601 pixel square(max-luminance). It is <*scene_luminance_log_grayscale*> file made from both the displayed file and its luminance calibration measurements. The next top-panel is <*retinal_contrast_log_grayscale*> rendering the retinal image.

Fig 2 (top-right) next is <*retinal_contrast_log_cmap*> Pseudocolor rendering with its Color-map on its right side. Black is the bottom at digit 0; rendering relative $\log_{10}$ value = −2.3, or 0% log_range. Blue is the midpoint at digit 128, rendering relative $\log_{10}$ value = −1.15, or 14% log_range. White is the top at $\log_{10}$ value = 0.0, or 100% log_range. This <*cmap*> rendering shows the rapid falloff of <*retinal_contrast_log*> with distance from the max-luminance square. Its quantitative <*retinal_contrast_log*> value can be identified by matching a pixel's color with that in Color-bar scale in the panel (right-side).

A different kind of LUT (3-3-2 RGB) is shown in the lower half of Fig. 3. (bottom-left) panel shows its scale [0,255]. Digit=0 in Pseudocolor is black (top-left); Digit=15 is (top-right, dark-cyan-blue); and Digit=255 is (bottom-right, yellow). Its Color Index emphasizes the visibility of gradients. It has 256 different colors. It illustrates glare's redistribution from the max-central square throughout the min-background. It was applied to <*retinal_contrast_log_grayscale*> (top-middle) using application *ImageJ®*.[6] This (3-3-2 RGB) LUT rendition is shown in Fig. 3 (bottom-middle).

The details throughout the min background are not visualized using <*cmap*> rendering; but are clearly visible in <3-3-2 RGB>. However, the boundary at the edge of the square is difficult to observe. The bottom-right panel identifies the location of that sharp input-edge using four quarter-image sections: (top) 3-3-2 RGB) <*scene_luminance_log*> and <*retinal_contrast_log*>; (bottom) max-square-alone, and min-background-alone using. The thin red band locates the max/min boundary, that has become a steep gradient after glare. The scene's sharp edge (top-left) has become a blurry gradient on the retina (top-right). The exact location of that edge is hard to find in the retinal image. The bands of constant *retinal-contrast* values are thinest at the max-min edge in the input. However, glare has influenced the boundary regions of both the square and the background. The square distributes 200 times (per/pixel) more glare than background pixels. The square's center is surrounded by max glare donors. However, adjacent to square's edge, the nearby half-max and half-min glare sources reduce the square-interior edge's *retinal-contrast*. The min-background-interior pixels receive limited glare from the larger background area; the square's glare falls off with distance from it. This combination is a high-slope gradient, not the discontinuity in the input. Vision has to use multi-resolution spatial-image processing to place the appearance of the apparent sharp edge. At the midpoint on the side of the square the max-side-pixel value is 240; min-side value is 237. The calibrated edge-ratio across the pair of boundary pixels is only 1.06 at this resolution.

Experiment and Results

Fig. 3-**Scene** (upper-left) combines Contrast and Todorovic [7] Assimilation Illusions. It is the image as displayed on the computer in Fig 1. Placing both Assimilation and Contrast one above the other in a target does not affect each other's appearance. Both Contrast and Assimilation appear indifferent to each other. Contrast and Assimilation, are influenced by relatively local-spatial composition of their Illusions. Throughout Fig. 3-**Scene**, all Black, segments appear uniform and identical, as do all White segments.

Contrast and Assimilation make the GrayROIs have location-specific changes in their uniform appearances. In Contrast, the Gray-in-White circle appears darker than the Gray-in-Black circle. In Assimilation, the Gray-in-Black-Foreground cross appears darker than the Gray-in-White one. Fig. 3-**Retina** (bottom_left) is the program's output image file: <*retinal_contrast_log_grayscale*>.

Numerical analysis of Retina vs. Scene

The blue arrows and red arrows in Fig. 3**Scene** indicate the locations of two horizontal digital (one-pixel high) scans across the input **Scene** and output **Retina** images of the Contrast Illusion's circles and Assimilation crosses. Glare changed the entire **Retina** range of linear *retinal_contrast* to 42:1 [log_range =1.6], compared with the input **Scene** range of 200:1 [log_range =2.3].

The <*scene_luminance_log*> values have identical horizontal scans at both blue and red arrows [log_range=2.3]. Along a horizontal scan of **Retina-**Contrast circle's centerline (blue arrows) the [log_ranges=1.55]. Along a parallel horizontal scan of Assimilation cross's centerline (red arrows) the [log_ranges=0.33]. Linear values are [Scene_range=200:1; Contrast_range=36:1; Assimilation_range=3.3:1] Assimilation segments have much lower range, and more rounded retinal edges.

Glare distorts <*scene_luminance*> arrays. Retinal GrayROIs are no longer equal. GrayROIs in Contrast and Assimilation begin with unequal <*retinal_contrast*> values. They are the input to receptors, that initiate neural-spatial transformations. Table 1 lists peaks and ranges of all four GrayROI segments. **Retina's** Contrast circles exhibits Glare's Paradox. The GrayROI-in-White (light blue arrow) appears darker despite more glare. As well, Gray-in-Black (darker blue) appears lighter despite less-glare light. Contrast GrayROI circles have uniform [*scene_luminances=77%log_range*]. In circles, <*retinal_contrast_log*> becomes GrayROI-in-Black peak of 77% [60% to 79%] log_range, and peak of 79% [78% to 95%] in Gray-in-White. The White surround adds more glare light to its Gray. The challenge is to understand why Contrast's more-light in Gray-in-White looks darker.

Assimilation does not exhibit Glare's Paradox

In circles Fig. 3-**Scene**(top-left) the max/min edges are a considerable distance from their centers (46 minute radius). The crosses are 10 times closer to max/min edges (4.2 minutes at nearest pixel). In Assimilation glare adds the most glare to crosses in Gray-in-White pixels (Table 1). Their peaks are further apart indicating larger glare distortions. In <*retinal_contrast_log*> crosses in Gray-in-White has peak of 86% max [81% to 94%] log_range; in Gray-in-Black has peak of 72% [60% to 88%]. In Assimilation, glare adds more light to segments that appear lighter; and less to Grays that look darker. Glare's changes in <*retinal_contrast*> helps to enhance computational appearance models of Assimilation.

Glare distorts uniforms input arrays of <scene_luminances>; glare makes them into variable gradient of light on receptors. Nevertheless, all White, and Black segments in Fig. 3-**Scene** appear to be constant and uniform Whites, and Blacks.

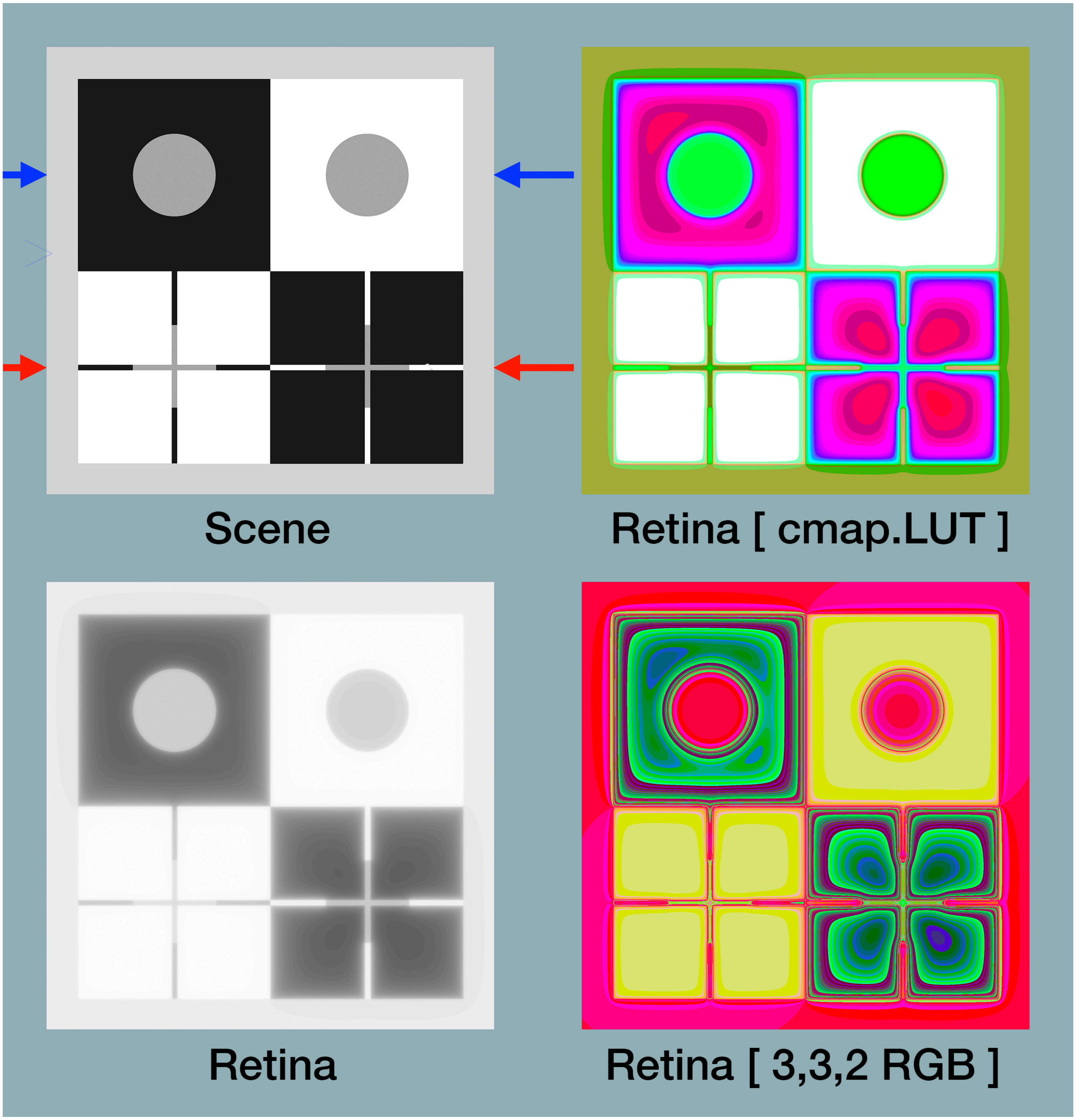

Fig. 3 Four Contrast+Assimilation files with different renditions of the target:

***Scene** (top-left) Appearance of display: Reproduction of Fig.1's Image 2 used to illustrate what the observer saw.*

***Retina** (bottom-left) displays (Fig.1's Image 6) the output of the convolution with the CIE GSF: <retinal_contrast_log_grayscale> used to make quantitative measurements of individual pixel values of the normalized pattern of light on receptors.*

***Retina [cmap.LUT]** (top-right) and **Retina [3,3,2.LUT]** (bottom-right) showing different Pseudocolor LUTs (Fig.1's Image 8) that make the patterns of glare's distortions of scene luminances visually apparent. While gradients in luminances on the retina are invisible, discriminable bands of constant color make the gradient's structure visible. All Fig.3 calculations used parameters [log_range=2.3], [padding=replicate].*

Contrast		Glare's Paradox
	Gray-in-Black	Gray-in-White
Peak [pixel count]	28,911	28,706
Peak [%log Max]	77%	79%
Range [%log Max]	60%-77%	78%-95%
Assimilation		**No Glare's Paradox**
	Gray-in-White	Gray-in-Black
Peak [pixel count]	3,196	3,668
Peak [%log Max]	86%	72%
Range [%log Max]	81%-94%	60%-88%

Table 1 lists GrayROI % log range values in Figure 2 ***Retina.*** *It shows quantitative data for GrayROI <retinal _contrast> image segments in Black, and in White surrounds for both Contrast and Assimilation Illusions. The table lists: pixel count; peak; and range of [% log max] GrayROI values.*

Glare's Paradox

Fig. 4 (top) shows the appearances of: Contrast+Assimilation, B&W Mondrian [8], and Checkershadow® [9] computer displays. It adds Negative displays of B&W Mondrian and Checkershadow made with (Photoshop's® negative function). Negative Illusions work very well. The Mondrian Negative has different patterns of edges, and has illumination from above. The "shadow" in Checkershadow's now appears to emit light. The [*cmap.LUT*] used in Fig.4(bottom-row) shows the complexity of <*retinal_contrast*> gradients and variable ranges of Glare Paradoxes.

In the Mondrian, the top-lighter circle ROI has *retinal_contrasts* (range = 22% to 33%max). The *bottom*-darker circle ROI (range=38% to 58%max). In the Negative Mondrian, the top-darker circle ROI has *retinal_contrasts* [20% to 33%] log_range. The bottom-lighter circle ROI [14% to 20%] log_range. Both Mondrians overcompensate for glare.

In the Checkershadow, the central-lighter ROI has *retinal_contrasts* [16% to 22%] log_range; top-darker ROI [24% to 36%] log_range. In the Negative Checkershadow, the central-darker ROI has *retinal_contrasts* [49% to 80%] log_range; top-lighter ROI [25% to 47%] log_range. Both Positive- and Negative-Checkershadows overcompensate for glare.

All five Glare's Paradox targets, have darker GrayROIs with more glare light. Their darker ROIs are in local regions with higher-than-average *scene_luminances*. The sequence is [greater *local_average_scene_luminance* regions ➜ greater_glare ➜ smaller_edge_ratios ➜ higher-slope *local_response_function* ➜ darker appearance].

Studies of glare in HDR scene showed very-large reductions of retinal-dynamic range in maximal-glare scenes. The input scene has [log_range=5.4]; after glare [log_range=1.5]. Replacing the max-luminance surround with min-luminance surround, retinal_contrast range becomes 3.7 log units.[2,10] In both max- and min-luminance surrounds, White segments had equal max-luminances, and appeared the same White. Black segments had the same Black appearance in both max- and min-surrounds.[10] However, Blacks had markedly different scene-luminances. In max-luminance surround, Black appearance segments were 3% max-luminance. In min-luminance surround, Black appearances were 0.002% max-luminance. Glare in max-luminance surround reduced White/Black range to [33:1]; exhibiting very-limited-range (high-slope) response function (e.g high-glare beach scenes). However, Glare in min-luminance surround reduced range to the much larger [5,000:1]; exhibiting very-wide-range (low-slope) response function (night scenes). Vision has variable scene_response_function to light on receptors that is scene dependent.[2,10]

In Glare's Paradox all of the darker GrayROIs are located in regions with greater than their local_average_scene_luminances (See Fig. 4-top row). Vision's local response function to light on receptors varies with scene_content. It has limited-range (high-slope) response_function in high-glare scenes. In Lightness Illusions, these darker GrayROI regions have glare-induced lower-ranges of local-retinal_contrasts, and have appearances associated

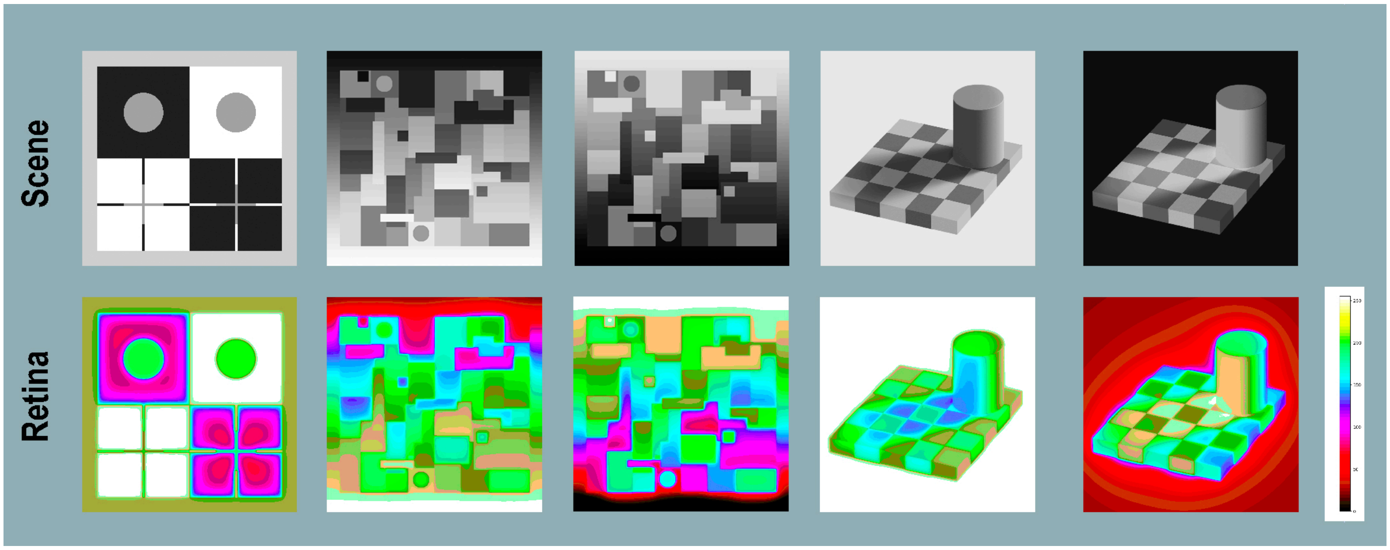

Fig 4. Contrast, B&W Mondrian's, and Checkershadow are five examples of Illusion's Paradox. Assimilation stands alone because it adds light to scene segments that appear lighter. (top-row) reproduction of target on display. (bottom-row) Program output showing the distribution of light on receptors: [retinal_contrast_ log_cmap]. Numerical analysis of Glare's Paradox shows that retinal_contrast adds more glare light to ROI segments that look darker in all five Illusion. (Adelson's Tower appears to shade the light in the positive; and emit the light in the Negative).

with high-slope visual-response functions. These higher contrast response functions generate darker appearances.

Glare's Paradox exhibits reciprocal properties for ROIs that appear lighter. All Contrast and Natural Scene examples have: [lower *local_average_scene_luminance* regions ➜ less_glare ➜ larger_edge_ratios ➜ lower-slope local *response_function* ➜ lighter appearance].

Glare's Paradox is not found in Assimilation segments. Glare adds more glare to segments that appear lighter; less light to segments that appear darker. The angular separation between max and min are smaller, and local *retinal_contrast_range* is smaller. Glare assists Assimilation's change in appearance. Assimilation Illusions improve with smaller angular size, unlike Contrast where observer matches are constant with viewing distance.[5]

Summary

Glare introduces a complex scene-depended transformation of all <*scene_luminances*> making a different spatial pattern of light on receptors, called <*retinal_contrast*> *arrays*. The convolution of *scene_luminances* with Vos and van den Berg's CIE 1999 GSF calculates high-resolution arrays of <*retinal_contrasts*>. The results show that uniform-luminance scene segments become low-slope gradients that are nearly invisible. Visual inspection of these arrays is misleading. Plots of digit values, histograms, and other numerical techniques are needed to analyze light falling on receptors.

Pseudocolor Look-up Tables are very helpful in visualizing the complexity of glare's spatial transformations. Neural spatial processes are the next spatial-image transformation that leads to appearances. Illusions and Natural Scenes demonstrate [Appearance≠scene-luminance]. Analysis of their patterns of light on receptors (*retinal_contrast*) shows that glare adds light to GrayROI segments that look darker. Contrast, Land's B&W Mondrian, and Adelson's Checkershadow all exhibit Glare's Paradox. In complex scenes, vision's second spatial transformation in the neural pathway overcompensates the effects of glare. Illusions' Gray regions-of-interest look darker despite increase glare light on receptors.

Assimilation Illusions are different. They add light to GrayROIs that appear lighter. More important, its small separations, and periodic designs create <u>local</u> high-glare and low-range *retinal_contrast* segments. Recall that the range of the scan between the red arrows has been glare reduced to 3.3 %max. Assimilation's most critical Challenge is not the appearances of GrayROIs. Its Challenge is how to predict the uniform appearances of Blacks. Recall as well, Contrast's scan between blue arrows has 36 %max range. Assimilation has 11 times smaller range on the retina. The challenge for Assimilation models is that "Blacks-in-Assimilation" appear in distinguishable from "Blacks-in-Contrast".

On the computer display, set to [range=200:1], the magnitude of glare's quantitative transformations are small compared to those in HDR images. Nevertheless, glare affects the sharpness of edges, and replaces uniform luminances with complex gradient patterns on the retina. The specific design of Contrast and Assimilation Illusions maximizes glare's magnitude, and its variability because the "rest of the scenes" were designed with only max- and min-luminances. Whites are the maximum donor of glare; and Blacks are the major receiver. Contrast Illusions have very different spacings of Whites-and Blacks compared with Assimilation. Local scene-content controls the important local glare-limits. The semi-global light distribution on receptors creates Glare's Paradox, and controls its variable local *response function* to light.

Illusions teach us that vision is scene dependent; that is, visual appearances vary with the local and global content of each scene's array of radiances. Intraocular glare and Color Constancy expands that lesson. The radiance, or luminance of a scene segment or a display pixel is insufficient information to calculate that segments appearance. The "rest-of-the-scene" matters. Models of appearance require all scene segments in their input data.

Scene independent models, that restrict scene measurements to one data sample can be useful in some restricted circumstances. Quanta catches can predict silver-halide film densities, but not in cameras with optical glare from lenses. CIE XYZ can predict color matches in a no-glare surround, but not in a Color Constancy experiment, or Natural Scenes, or images made with optical lenses.

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