Constancy in Natural Scenes: How Neural Contrast cancels Glare

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http://mccannimaging.com/Retinex/Talks.html
Vision has two powerful spatial processes that transform scene radiances. The first transform is the degradation of the retinal image by intraocular glare in normal observers; the second is the spatial enhancement by post-receptor neural mechanisms. First, veiling glare transforms natural scenes into lower-contrast retinal images, depending on the content of the scene (radiance and spatial distribution). Beach scenes (mostly very high reflectances, and sky) have considerable glare, and hence, low-contrast retinal images. Alternatively, stars at night have little glare, and high-contrast on the retina. Second, neural spatial processes more than compensate for optical glare. High-glare beach scenes in the normal eye appear to have high contrast. The appearance of retinal quanta catch varies considerably with scene content. Normal observers do not see glare in everyday life, but glare masks the powerful scene-dependent (spatial neural) transforms of natural scenes.
HDR Constancy
Neural contrast cancels veiling glare

- Glare in normal observer - not low vision
- Glare varies with scene content
  - Glare spread function - calculate retinal image
    - Beach scene - low contrast
    - Stars at night - high contrast
- Apparent Contrast
  - Highest Contrast - Beach
  - Lowest Contrast - Stars at night
Appearance of receptor quanta catch in normal observer

- Different responses
  - A. Spots of light - Hipparchus, Fechner, Stevens
  - B. Center surround - Weber, Wallach
  - C. Natural image - Land, HDR imaging
    - Glare and neural contrast
    - Cancelation of two spatial processes
Constancy in normal observer

• Different responses
  • A. Spots of light - none
  • B. Center surround - variable
  • C. Natural image - considerable, but has limits
Hipparchus of Nicea
great-grandfather of psychophysics

○ Stellar magnitude
  ○ 2nd century BC
    ○ Hipparchus of Nicea,
      ○ quantized the appearance of stars into six brightness magnitudes
  ○ 138 AD
    ○ “Almagest” of Claudius Ptolomy, expansion
  ○ 14th century Tycho Brahe
  ○ 1721 Halley
  ○ 1856 Pogman - influenced by Weber
Stellar Magnitude

- Halley (1721) & Pogman (1856)
  - from 100,000:1 change in luminance (cd/m²)
  - 100:1 to change in appearance
Bodmann H, Haubner P & Marsden A (1979),
A Unified Relationship between Brightness and Luminance,
CIE 50, CIE Proc. 19th Session (Kyoto), 99-102,
Bodmann 2° spot

spot > surround

0 cd/m² surround
300 cd/m² surround

Stellar Magnitude

2° spot
vary Luminance

180° surround
Luminance = 300

Log luminance

Brightness
Bodmann 2° spot

spot < surround

- Neural Contrast
- High slope

2° spot
vary Luminance

180° surround
Luminance = 300

Log luminance

Brightness

0 1 2 3 4 5

0 cd/m² surround
300 cd/m² surround
300 cd/m²
spot < surround

- 0 cd/m² surround
- 300 cd/m² surround
- 300 cd/m² surround

Surround 10,000 cd/m²

2° spot vary Luminance

180° surround Luminance = 300
Luminance = 10,000

Brightness vs Log luminance graph.
Different mechanisms

- Maximum
  
  \[10:1 \text{ (luminance)} \rightarrow 2:1 \text{ (appearance)}\]

- \(< \text{ Maximum}\)

  Spatial Contrast: Surround > Spot

  \[2:1 \text{ (luminance)} \rightarrow 2:1 \text{ (appearance)}\]
Bodman 2° spot
spot < surround

Neural Contrast
High slope

Hipparchus line

Maxima

300 cd/m²

Neural Contrast spatial mechanisms
Quanta Catch + Adaptation

Contrast

spatial mechanisms
Match gray areas to standard target

- TSD-1 [8 areas on white]
- TSD-2 [8 areas on gray]
- TSD-3 [8 areas on black]

Equally spaced Lightness

3 targets with 3 surrounds

Left eye

Right eye
Match gray areas to standard target

- TSD-1 [8 areas on white]
- TSD-2 [8 areas on gray]
- TSD-3 [8 areas on black]

3 targets
with
3 surrounds

Equal Radiances

Left eye

Right eye
OD = 0.00

0.4

0.8

2.0

3.3

5 levels of illumination

Left eye

Right eye
5 levels of illumination

Left eye

Right eye

Dynamic range ~5 log units
Plot all 8 areas from each illumination.
Plot each area from all illuminations.

White Surround Match

Match

0 1 2 3 4 5 6 7 8 9 10

Luminance ft-L

0.01 0.1 1 10 100 1000 10000

Same data - Different lines
Illumination, Constancy & Surround

Hipparchus line

Match

Log Luminance
Illumination, Constancy & Surround

Log Luminance

Match

Hipparchus line

Neural Contrast
Maximum sets position on the Hipparchus line
Areas < Maximum
Surround sets slope of the Neural Contrast

Grays get darker FASTER with more white!
<table>
<thead>
<tr>
<th>Lightness Units</th>
<th>W-B Range</th>
<th>Test Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>1.8</td>
<td>2.1</td>
</tr>
<tr>
<td>2.1</td>
<td>2.5</td>
<td>3.5</td>
</tr>
<tr>
<td>2.4</td>
<td>3.9</td>
<td>3.9</td>
</tr>
</tbody>
</table>

- $3.9 - 1.5 = 2.4$ Lightness units
- $2.4$ units out of $9.0 = 28\%$ W-B range
- Test square = $2.5^\circ$

**Constant stimulus**
**Change spatial arrangement**
**Goal:** Model Lightness

### Ratio-Product-Reset-Average

- **Radiances**
- **$R_{x,y}$**
- **$R_{x',y'}$**

**Ratio** \( \frac{R_{x',y'}}{R_{x,y}} \)

**Reset**

**Old Product** $\text{OP}_{x,y}$

**New Product** $\text{NP}_{x',y'}$

**: NP_{x',y'} = \text{OP}_{x,y} \times \left[ \frac{R_{x',y'}}{R_{x,y}} \right]$$

**Reset:** If $\text{NP}_{x',y'} > \text{Max}$, $\text{NP}_{x',y'} = \text{Max}$

### Table:

<table>
<thead>
<tr>
<th>Reflectance</th>
<th>Illumination Gradients</th>
<th>Simultaneous Contrast</th>
<th>Surround</th>
<th>Edges plus Gradients</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Average</td>
<td>Flat</td>
<td>Gray on White</td>
<td>White</td>
<td>Up</td>
</tr>
<tr>
<td>Normal</td>
<td>Horizontal</td>
<td>Simultaneous Contrast</td>
<td>Gray</td>
<td>Flat</td>
</tr>
<tr>
<td>Low Average</td>
<td>Horz +Vert</td>
<td>Albers</td>
<td>Black</td>
<td>Down</td>
</tr>
</tbody>
</table>
Veiling glare increases gray luminance.

Contrast decreases gray appearance.

Contrast offsets glare.
glare \((at \ x, y)\)

- Sum of stray light from other scene elements
  - (all other pixels)

- Each contribution depends on:
  - radiance
  - distance
  - Glare Spread Function (GSF)

![Graph showing the Glare Spread Function (GSF) from Vos et al. 1976. The x-axis represents the distance from the pixel, and the y-axis represents the fraction scattered. The graph shows a rapid decrease in scattered light as the distance increases.](image-url)
1980 - Pre FFT calculation


Stiehl calculated the retinal image and compared it to the display.

Retinal Dynamic Range ≠ Discrimination
Cube-root Range Compression

\[ L^* = 116 \left( \frac{Y}{Y_n} \right)^{1/3} - 16 \]
Log quanta catch on the retina is proportional to lightness appearance.
The cube-root function in CIELAB and CIELUV is caused by scattered light (Stiehl et al.)

$L^* \neq \text{a psychometric function, rather optics}$
Munsell (UCS)
Uniform Color Space
Y, x, y
CIE 1931 Color Space
CIE Yxy → Munsell

* Ignore Lab labels (I could not edit Bob Sobol’s Plot routine)

Fit the Munsell Book’s data to a model of vision. You can solve for the transform that places all the Munsell chips in their defined locations in Uniform Color Space (UCF).

Lightness (log retinal) Linear Log Cube root
We know the cone quanta catch from:

- the paper’s spectral reflectance of the paper
- the spectrum of the illumination
- the LMS cone responses to the each paper

We know the papers position in UCS from observer data

Solve for best transform: (normalized cube root cone quanta catch) to UCS position
Solve for position in color space

\[
V = 0.5 \times \left[ (L_{cone})^{1/3} + (M_{cone})^{1/3} \right]
\]

\[
R_{2BG} = 7 \times \left[ (L_{cone})^{1/3} - (M_{cone})^{1/3} \right]
\]

\[
Y_{2PB} = 2 \times \left[ - (L_{cone})^{1/3} + 2 \times (M_{cone})^{1/3} - (S_{cone})^{1/3} \right]
\]

Used cube-root of integrated cone responses and normalized within cone type.

That is = log cone quanta catch at the retina = cone response
At the retina
Spacing in the Munsell Book

\[ V = 0.5 \times \left[ (L_{cone}) + (M_{cone}) \right] \]

\[ R_{2BG} = 7 \times \left[ (L_{cone}) - (M_{cone}) \right] \]

\[ Y_{2PB} = 2 \times \left[ (M_{cone} - L_{cone}) + (M_{cone} - S_{cone}) \right] \]

Used cube-root of integrated cone responses and normalized within cone type.
Scene Colorimetry

V = glare

Optical

→ Munsell

R2BG = 7(L-M) cone
Y2PB = 2(2M-L-S) cone

Neural
Appearance of receptor quanta catch in normal observer

- Different responses
  - A. Spots of light - Hipparchus
  - B. Center surround
- C. Natural image
  - Scene content and glare
  - Cancelation of two spatial processes
HDR Test Setup

7 Fluorescent lamps

Opal plexiglass

1.0, 2.0, 3.0 ND circles

Opaque mask with 4 holes

4 Kodak step-wedges

18,619:1 range
digit 255 = 2094.2 cd/m²

digit 0 = 0.11 cd/m²

Goal Image

\[
\frac{2094.2 \text{ cd/m}^2}{0.11 \text{ cd/m}^2} = 18,619
\]

Synthetic HDR (High-Dynamic Range) Images

18,619:1

Range in one scene
Targets

18,619:1

20:1
16 sec exposure - Target 1 scale Black
16 sec exposure - Target 4scaleBlack
16 sec exposure - Target 4scaleBlack
Constant Luminance - Variable Surround
Magnitude estimates (100-1)
Magnitude estimates (100-1)

Appearance vs. Luminance

Hipparchus line
Constant Stimuli

Constant Appearance

Appearance vs. Luminance

Magnitude Estimation

Log Luminance (cd/m²)

Constant Stimuli
White Surround adds Veiling Glare
• Luminance does not correlate uniquely with appearance

• No global tone scale can render the HDR appearance

• Psychometric function = global tone scale
Separate Glare from Contrast

- White surround
  - adds glare
  - changes surround (simultaneous contrast)

We need a new range target

- Vary dynamic range with
  - contrast surround
Single & Double Density Transparencies

Single =

2.7 \log_{10} \text{ range}

Double =

(superimposed)

5.4 \log_{10} \text{ range}

Use 1/2 White and 1/2 Black Surround
A. Rizzi and J. McCann (2009)

Separate HDR from Glare and Contrast
## A. Double Density Film Transparencies

Single = 2.7 log\(_10\) range

Double = (superimposed) 5.4 log\(_10\) range

<table>
<thead>
<tr>
<th>Target</th>
<th>Max cd/m(^2)</th>
<th>Min cd/m(^2)</th>
<th>Range:1</th>
<th>%Average cd/m(^2)</th>
<th>O.D. Min</th>
<th>O.D. Max</th>
<th>O.D. Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Contrast</td>
<td>6,680</td>
<td>13.6</td>
<td>490</td>
<td>50.01%</td>
<td>0.20</td>
<td>2.89</td>
<td>2.69</td>
</tr>
<tr>
<td>Double Contrast</td>
<td>4,215</td>
<td>0.018</td>
<td>239,883</td>
<td>50.00%</td>
<td>0.40</td>
<td>5.78</td>
<td>5.38</td>
</tr>
</tbody>
</table>
Center/Surround Basic Unit

Gray test areas 12% (small differences)

Fixed contrast surround 88%
A. HDR Target - 250,000:1
Average surround - Half White & Half Black

Constant surround 88% area
Gray test areas 12% area
(small differences)

90° rotation
• A. HDR Targets with varying glare - Vary Surround (88% area)

Scene Dynamic Ranges at Cornea

200,000:1 5.3 log units
250,000:1 5.4 log units
630,000:1 5.8 log units
# Magnitude Estimation

<table>
<thead>
<tr>
<th>Units</th>
<th>Estimates</th>
<th>Observers</th>
<th>Trials per Observer</th>
<th>Target Angle</th>
<th>Gray Square Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>40</td>
<td>5</td>
<td>5</td>
<td>19.1° by 15.5°</td>
<td>0.8°</td>
</tr>
</tbody>
</table>
White[100] = 0.0 rOD - Black [1] = 2.89 rOD
2.3 log_{10} units

50% white surround

relative optical density

magnitude estimation

50% Double Density

50% Single Density
Relative optical density magnitude estimation

White Double Density
White Single Density

2.0 $\log_{10}$ units

100% white surround
Limited opportunity for improved reproductions

Better dark grays in night scenes

5.0 log_{10} units

Over 20 not big improvement

Limited opportunity for improved reproductions
Computational models of vision start with the quanta catch of retinal receptors.
Glare Spread Function

Vos, J.J. and van den Berg, T.J.T.P,

\[
\frac{L_{eq}}{E_{gl}} = \left[1 - 0.08 \cdot (A/70)^4\right] \cdot \left[\frac{9.2 \cdot 10^6}{\left[1 + \left(\frac{\theta}{0.0046}\right)^2\right]^{1.5}} + \frac{1.5 \cdot 10^5}{\left[1 + \left(\frac{\theta}{0.045}\right)^2\right]^{1.5}}\right] + 2.5 \cdot 10^{-3} \cdot p
\]

\[
+ \left[1 - 1.6 \cdot (A/70)^4\right] \cdot \left[\frac{400}{\left[1 + \left(\frac{\theta}{0.1}\right)^2\right]} + 3 \cdot 10^{-8} \cdot \theta^2\right] + p \cdot \left[\frac{1300}{\left[1 + \left(\frac{\theta}{0.1}\right)^2\right]^{1.5}} + \frac{0.8}{\left[1 + \left(\frac{\theta}{0.045}\right)^2\right]^{0.5}}\right]
\]

**PIGMENT**

- Blue eyed Caucasian: 1.21
- Blue green Caucasian: 1.02
- Mean over all Caucasian: 1.00
- Brown eyed Caucasian: 0.50
- Non Caucasian with pigmented skin and dark brown eyes: 0.00

Ivar Farup and T. van den Berg
Calculate retinal luminances

CIE Veiling Glare Standard

J. Vos and T. van den Berg (1999) collected a series of measurements for the 1999 CIE report. We used the formula referred to as number eight. The formula is:

\[
\frac{L_{eq}}{E_{gl}} = \left[1 - 0.08\left(\frac{A}{70}\right)^4\right] \left[\frac{9.2 \times 10^6}{[1 + (\theta / 0.046)]^{1.5}} + \frac{1.5 \times 10^5}{[1 + (\theta / 0.045)]^{1.5}}\right] + \\
\left[1 - 1.6\left(\frac{A}{70}\right)^4\right] \left[\frac{400}{[1 + (\theta / 0.1)]^{2}} + 3 \times 10^{-8} \cdot \theta^2\right] + \rho \left[\frac{1300}{[1 + (\theta / 0.1)]^{1.5}} + \frac{0.8}{[1 + (\theta / 0.045)]^{0.5}}\right] + 2.5 \times 10^{-3} \cdot \rho
\]

where \(\theta\) is the viewing angle from the point from which the light is spread causing the veiling glare, \(A\) is the age of the observer, and \(p\) is his/her iris pigmentation. In the calculation we used an age of 25 and brown Caucasian pigment.

We converted this formula into a convolution filter.

• B. CIE Glare Spread Function
B. Calculate retinal luminances:

Scene content controls range on the retina.

Calibration Technique
Dynamic Range = 5.4 OD
or 251,189:1

False-color LookUpTable (LUT)
• Pseudocolor Look-Up Table (LUT)

Target Contrast

Single Density

Optical Density

Double Density

Range 500:1

Range 250,000:1

Visualize HDR targets
• Glare reduces range of light on retina

Retinal Contrast

Single Density  
Optical Density  
Double Density

Range 100:1  
Range 150:1

Visualize retinal images
• Blacks appear equal & Whites appear equal

Range 250,000:1

Range 30:1

Target Contrast

Retinal Contrast

uniform areas

gradients

W/B edge ratios

constant

variable

Retinal image is a spatial transform of scene
<table>
<thead>
<tr>
<th></th>
<th>DD white OD</th>
<th>DD black OD</th>
<th>W/B contrast OD</th>
<th>W/B edge ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td>0.00</td>
<td>5.4</td>
<td>5.40</td>
<td>251,188.64</td>
</tr>
<tr>
<td>DD 64x</td>
<td>0.08</td>
<td>1.02</td>
<td>1.24</td>
<td>17.46</td>
</tr>
<tr>
<td>DD 32x</td>
<td>0.09</td>
<td>0.89</td>
<td>1.08</td>
<td>12.02</td>
</tr>
<tr>
<td>DD 16x</td>
<td>0.17</td>
<td>0.61</td>
<td>0.86</td>
<td>7.31</td>
</tr>
<tr>
<td>DD 8x</td>
<td>0.24</td>
<td>0.43</td>
<td>0.59</td>
<td>3.93</td>
</tr>
<tr>
<td>DD 4x</td>
<td>0.25</td>
<td>0.51</td>
<td>0.32</td>
<td>2.11</td>
</tr>
<tr>
<td>DD 2x</td>
<td>0.35</td>
<td>0.47</td>
<td>0.22</td>
<td>1.64</td>
</tr>
<tr>
<td>DD 1x</td>
<td>0.46</td>
<td>0.53</td>
<td>0.16</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Optical densities of variable size squares
Edges become gradients on the retina
• Compare appearances vs. retinal image:

Measure appearance by magnitude estimation

• C. Compare scene vs. retinal image
Appearance = m*log(retinal luminance)

```
Retinal Contrast

0%W  50%W  100%W

Scene Dependent Contrast
```
30:1

Retinal Range = 1.5 log units
100:1

Retinal Range = 2.0 log units

Retinal Range = 1.5 log units
Range of response varies with scene content

10,000:1

Retinal Range = 4 log units

Retinal Range = 2.0 log units

Retinal Range = 1.5 log units
<table>
<thead>
<tr>
<th>%White</th>
<th>Stiehl, et al.</th>
<th>100%</th>
<th>50%</th>
<th>0%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range (OD) at cornea</td>
<td>opaque blacks</td>
<td>5.3</td>
<td>5.4</td>
<td>5.8</td>
</tr>
<tr>
<td>Range (OD) at retina</td>
<td>1.4</td>
<td>1.4</td>
<td>2.0</td>
<td>3.5</td>
</tr>
<tr>
<td>Usable Range (OD) MagEst (100 to 1)</td>
<td>2.0</td>
<td>2.3</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>m slope</td>
<td>71.4</td>
<td>71.4</td>
<td>50</td>
<td>27</td>
</tr>
</tbody>
</table>
Two scene-dependent spatial mechanisms: glare and contrast. Glare masks the strength of spatial contrast.
Scene: 1,000,000:1
Retina: 100:1
Appearance: 1,000:1

Spatial Glare
Scene Dependent
Lower Contrast

Spatial Contrast
Scene Dependent
Higher Contrast
There is no single psychometric response of the eye.

Appearance varies with scene content.

- **Different responses**
  - **A. Spots of light - Hipparchus**
    - no glare*
    - only contrast with intrinsic receptor noise
  - **B. Contrast (Center & Surround) Hipparchus +**
    - Different slope with scene content
  - **C. Complex & Natural images - Two opposing processes**
    - Hipparchus & bigger changes in slope
    - Glare and Neural Contrast
    - Cancelation of two spatial processes
HDR Constancy
Conclusions

• Responses to light
  • Maxima - Hipparchus line - low slope
  • < Maxima - high slope
  • Local Maxima fall on Hipparchus line
  • Local Maxima + variable slope contrast explains Lightness constancy
Conclusions

• Retinal image

• Glare varies with scene content
  Greater glare -
  lower retinal contrast -
  higher slope neural contrast

Lower glare -
  higher retinal contrast -
  lower slope neural contrast

• Computational Models
  Neural Contrast >> larger
  using retinal image
Conclusions

• Glare and Neural Processing
  • Glare is important in understanding UCS
  • $L^*$ cube root is optical
Constancy in Natural Scenes: How Neural Contrast cancels Glare

Thank you

http://mccannimaging.com/Retinex/Talks.html
Luminance  Glare  Sensors  Spatial comparisons

Glare → Neural Contrast
Two opposing spatial mechanisms