Surface color perception in 3D scenes: Estimating, representing and discounting the light field

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Reprints
http://www.psych.nyu.edu/maloney/index.html
Light
Shape
Material
Color

George de la Tour,
*The Magdalene with the Smoking Flame*

c. 1636-1638

Los Angeles County Museum of Art
Surface Color Perception:
The Bad News
The Mondrian Singularity

Piet Mondrian, Composition with Red, Yellow, Blue and Black
1921, Gemeentemuseum, The Hague
The Mondrian Singularity

Piet Mondrian, Composition with Red, Yellow, Blue and Black
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The Mondrian Singularity

Piet Mondrian, Composition with Red, Yellow, Blue and Black
1921, Gemeentemusuem, The Hague
Surface Color Perception: The *Really* Bad News

Don’t know how …
Surface Color Perception: Things get Even Worse ...

3D ...
Surface Color Perception in 3D
Surface Color Perception: It’s Really that Bad ...
Lumière naturelle au dessus de la Mosquée de Paris

Françoise Viénot, 2005
Surface Color Perception:
A Ray of Hope ...
The Mondrian Singularity

Piet Mondrian, Composition with Red, Yellow, Blue and Black
1921, Gemeentemuseum, The Hague
A Ray of Hope

In 3D the problem looks harder …

BUT

More information about spatial and spectral distribution of light (easier?)
Earlier Work

Recent Work

• Abstract, Full Paper: PDF(1,133KB)

Binocular Rendered -- Real
Experiment 1

Perceived orientation and Perceived Albedo (‘Lightness’)

Lightness Constancy

Discounting light intensity ....
Lightness Constancy

\[ \hat{\alpha} = \frac{L}{E} \]

Estimate of albedo  \( \rightarrow \hat{\alpha} \)

Luminance

Total light intensity
Lambertian Model

\[ L = \left[ E_P \cos(\theta) + E_D \right] \times \alpha \]

- \textit{Punctate Light}
- \textit{Diffuse Light}

\( \alpha \) represents the \textit{albedo} and \( E_P \) and \( E_D \) are the \textit{luminance} components for punctate and diffuse light, respectively.
Lightness Constancy

Discounting surface orientation?
Geometric Correction Factor

\[ \hat{\alpha} = \frac{L}{E} \Gamma(\theta, \pi) \]
Lightness Constancy

\[ \hat{\alpha} = \frac{L}{E} \Gamma(\theta, \pi) \]

- Estimate of albedo
- Luminance
- Geometric correction function
- Total light intensity
Experiment 1

Orientation cues

Stereo disparity
Linear perspective
Experimental Apparatus

crossed fusion

uncrossed fusion
Experimental Apparatus

Stereoscope

virtual objects
Stimulus

Rendered Stereo Pairs (RADIANCE)
Target Patch Orientations

\[ R \left( \alpha \right) \]

Diffuse Light

Punctate Light
Target Patch Orientations

R: -50°
Target Patch Orientations

R: -40°
Target Patch Orientations

R: -30º

Diffuse Light

Punctate Light

E

D
Target Patch Orientations

R: 0°
Target Patch Orientations

R: 30°

Diffuse Light

Punctate Light

D

E
Target Patch Orientations

R: 40º

Diffuse Light

Punctate Light
Target Patch Orientations

R: 50º

Diffuse Light

E

Punctate Light

D
The Tasks

On each trial …

Judge orientation
Judge lightness
Orientation Judgment

Monocular gradient probe (constrained)
Lightness Judgment

High-resolution gray scale, order randomized on each trial.
Experiment 1

• 20 repetitions of each condition
• $20 \times 7 \times 2 = 280$ trials per observer
• 6 naïve observers
Dependent Measures

\( \hat{R} \)  \hspace{1cm} \text{Perceived orientation}

\( \hat{\Lambda} = \frac{\text{Lum}^{\text{Setting}}}{\text{Lum}^{\text{Target}}} \)
\[ \hat{\Lambda} = c \Gamma (\theta, \pi) \]

Lightness setting ratio
Ideal Observer

\[ \hat{\Lambda} \]

\[ \psi^P \]

\[ \psi^P \]

\[ \psi^P \]

luminance match
The punctate light is *behind* the observer, not visible.

What if the observer misestimates the direction or the intensity of the punctate light?
(1) Error in estimated light direction $\alpha$
Ideal Albedo Estimation with Imperfect Information

\[
\hat{\alpha} = \frac{L}{E} \Gamma(\hat{\theta}, \hat{\pi})
\]

- Estimate of albedo
- Luminance
- Geometric correction function
- Light intensity
Not-so-Ideal Observer

\[ \hat{\Lambda} \]

Errors in estimating light azimuth ....
Errors in estimating punctate-total ratio $\pi$ ....
Experiment 1: Conclusions

• Orientation estimates close to veridical

• Perceived orientation influences lightness

• Estimates of light direction and punctate-to-total ratio not accurate

• Observers discount an equivalent lighting model (Brainard, 1998)

Experiment 2

Perceived Orientation and Perceived Color of Matte Surfaces

Scenes

Diffuse light source

Punctate light source

$E_P$

$E_D$

Viewer

$n$

$\alpha$

$\theta$

$\nu$
Scenes
Task: Achromatic Setting
Experiment 2

- 20 repetitions of each condition
- 2 light locations
- 10 rotations (5 azimuth, 5 elevation)
- 4 naïve observers
Blue-Yellow Balance Settings

$\Lambda^B$

“How blue the light impinging on the test patch seems to be …”
Coordinates

ψ rotation

ϕ rotation
Ideal Observer

punctate on LEFT

\[ \Lambda^B \]

\[ \psi_T \quad \varphi_T \]

-15

30

punctate on RIGHT

\[ \Lambda^B \]

\[ \psi_T \quad \varphi_T \]

15

30
Azimuth Estimates
Conclusions: Experiment 2

In scenes with a punctate and diffuse light sources differing in chromaticity,

• Observers partially discount illumination changes with orientation

• Observers effectively estimate information about the spatial and chromatic distribution of illumination in the scene
Conclusions: Experiment 2

In scenes with a punctate and diffuse light sources differing in chromaticity,

• Observers partially discount illumination changes with orientation

• Observers effectively estimate information about the spatial and chromatic distribution of illumination in the scene

How?
Experiment 3

Changes in incident light with changes in surface orientation

Changes in incident light with changes in surface location

Pieter de Hooch, The Mother (1659-1660) Gemäldegalerie Berlin
Condition A: No specular cues
Condition B: Specular cues
Lightness (Normalized)

Depth

○ no specular cues
● specular cues
Conclusions: Experiment 3

• Observers detect illumination changes from one location to another in a scene

• They partially discount illumination changes with location

• Addition of specular cues to illumination improves lightness constancy
Experiment 4

Cues to illuminant direction

How are observers estimating light source layout and chromaticities?

Estimating the Punctate-Total Ratio

\[ \pi = \frac{E^P}{E} \]

\[ E = E^P + E^D \]

Recall Exp. 1
Some candidate cues for estimating the punctate-total ratio
Four Conditions
One measure of use of cue:

Can we get a reliable estimate of direction to the light source when only that cue is present?
Cast Shadows

Shading

Highlights

All Cues
Conclusions: Experiment 4

• Most observers use specular highlight cue and cast shadow cue.

• Shading cue only used by one observer

• Observers combine information from multiple cues to get an estimate that is less variable than that of either cue alone (effective cue combination)
Experiment 5

Light Model Complexity

*How much of the spatial variation in the illumination does the visual system represent?*

Maloney, L. T., Boyaci H., Doerschner, K. (2005), Representing the spatial and chromatic distribution of the illuminant in scenes with multiple punctate chromatic light sources. (VSS 2005)

Light Model Complexity

\[ \varphi \]

\[ \psi \]

\[ 0^\circ, 90^\circ, 180^\circ, 360^\circ \]

\[ 0^\circ, \pi, 2\pi \]
Spherical Harmonics

The analogue of Fourier series on a sphere ...
SH Series Expansion

Light

\[ \sum \left\{ \begin{array}{c}
a_1 \\
a_2 \\
a_3 \\
a_4 \\
a_5 \\
a_6 \\
a_7 \\
a_8 \\
a_9 \\
\end{array} \right\} \times \begin{array}{c}Y_{00} \\
Y_{10} \\
Y_{11e} \\
Y_{11o} \\
Y_{20} \\
Y_{21e} \\
Y_{21o} \\
Y_{22e} \\
Y_{22o}
\end{array} \] etc
Spherical Harmonics

We can also represent spatial variation in the color of the illuminant …
• Spherical Harmonics \( Y_{nm} \)
• Spherical Harmonics $Y_{nm}$

- $Y_{00}$
- $Y_{10}$
- $Y_{11e}$
- $Y_{11o}$
- $Y_{20}$
- $Y_{21e}$
- $Y_{21o}$
- $Y_{22e}$
- $Y_{22o}$

$I(\phi, \psi)$
The visual system represents only the component of illumination captured by the one-bump subspace.
The One-Bump Subspace
\[ \mathcal{L}_4 \text{ The One-Bump Subspace} \]

linear combinations of ...
The One-Bump Subspace

Linear combinations of ...

Rotation around equator ...
$\mathcal{L}_4$ The One-Bump Subspace

linear combinations of ...
The One-Bump Subspace

linear combinations of ...

rotation vertically ...
$\mathcal{L}_4$ The One-Bump Subspace

$\mathcal{L}_4$ is closed under rotation

$\mathcal{L}_4$ can represent illumination in scenes with one ‘bump’ of illumination
One-bump subspace conjecture

The visual system represents only the component of illumination captured by the one-bump subspace
One-bump subspace conjecture

Equivalent: the visual system can only compensate for one punctate source, not two or more.
Light Configurations

160°

90°
Predictions

Expansion of light model (punctate sources)
\[ \psi_T = 0^\circ \]
$\psi_T = -30^\circ$
\[ \psi_T = -65^\circ \]
$160^\circ$

$\psi_T = 0^\circ$
$\psi_T = -30^\circ$
$\psi_T = -65^\circ$

$160^\circ$
Task: Achromatic Setting
Dependent Measure

Blue Balance Settings

\[ \Lambda^B \]

Think of it as the visual system’s estimate of how blue the light absorbed by the surface is …
Design

• 2 light configurations

• 9 test patch rotations (azimuth)
  -65 -45 -30 -10 0 10 30 45 65

• 20 repetitions of each condition

• 4 naïve observers
Predictions

\[ \Lambda_B \]

\[ \psi_T \]

-60 -30 0 30 60

90°

\[ \Lambda_B \]

\[ \psi_T \]

-60 -30 0 30 60

160°
Results
Data 160° Condition

$\Lambda_B$

-60  -30  0  30  60

$\psi_T$
Data  $160^\circ$ Condition

$\Lambda_B$

$\psi_T$

-60  -30   0   30   60
Data 160° Condition

\[ \Lambda_B \]

\[ \psi_T \]

-60 -30 0 30 60

160°
Data 160° Condition
Data 160° Condition

![Diagram of a top view and a graph showing lattice constants and errors in blue, with a topview of a model with a ball, a cylinder, and a rectangular prism. The graph on the right indicates lattice constants from -60° to 60° with 160° data, and the top view model shows a perspective from above with a yellow dot and a green, black, and red ball.](image)
Data 90° Condition

\[ \Lambda_B \]

-60  -30  0  30  60

\[ \psi_T \]
Data 90° Condition

\[ \Lambda_B \]

\[ \psi_T \]

-60  -30   0   30   60

90°
Data 90° Condition

\[ \Lambda_B \]

\[ \psi_T \]

-60  -30   0   30   60
Data 90° Condition

\[ \Lambda_B \]

\[ \psi_T \]

-60  -30   0   30   60

90°
Hypothesis: the visual system can only compensate for one punctate source, not two or more.
Hypothesis: the visual system can only compensate for one punctate source, not two or more.
One bump is not enough ...
$\mathcal{L}_9$ The Two-Bump Subspace

- Y00
- Y10
- Y11e
- Y11o
- Y20
- Y21e
- Y21o
- Y22e
- Y22o
Conclusions: Experiment 5

- Observes discount illumination in scenes with 2 punctate sources

- Visual system can represent spatial frequency information in the illumination up to the 9th spherical harmonic component

Recall:

- With a 9D subspace representation of the illumination a visual system is perfectly capable of compensating for the variations in luminance tested in this experiment as long as a Lambertian surface is concerned

- Such a system would be well adapted to the physics of light of matte surfaces
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