The Human Components of Image Systems

Many of the images in this tutorial are from
Wandell, Foundations of Vision, Sinauer Press
PDF of slide presentation is at www.imageval.com

Brian Wandell
Psychology and EE
Stanford University

Web-sites
Consulting: www.imageval.com
Research: white.stanford.edu
The Human Components of Color Systems

Color imaging systems are designed to convert optical and electrical signals into a desired perceptual effect. To design good color systems, one must understand the electronic and human components of the color-imaging pathway. This course introduces human color vision fundamentals and their influence on the design of color systems.

The course is designed for people entering the field of color engineering, or those who have worked on color technologies without the benefit of a course on human perception. The material in this course will serve as a background to various color technologies. Specifically, the student will learn about

- **Color matching** and trichromacy, the basis of the CIE color system
- **Spatial encoding** in human retina, the basis of color compression standards
- The color signals carried in the human brain, the basis of neurological color deficits
- **Visual adaptation** to changes in the environment, the basis of color balancing algorithms

Following this course, the student will have a better understanding of which aspects of color technology are fundamental and which are comprises necessary to ship product.

Professor Brian A. Wandell teaches at Stanford University where he founded the Image Systems Engineering Program (isep.stanford.edu). He is a co-founder of the consulting firm ImagEval (www.imageval.com) and a member of the technical advisory board of the digital pixel sensor company, Pixim (www.pixim.com). He is also a member of the Stanford Neurosciences Program where he teaches about the visual pathways and neuroimaging. He is the author of a textbook on human vision (Foundations of Vision, www.sinauer.com).
Tutorial Outline

- Introduction: Appearance and Computation
- Wavelength encoding and the photoreceptors
- Spatiotemporal sensitivity and the retina
- Color coding and visual cortex
- Visual Adaptation
Turning the Tables
(R.N. Shepard)
Fraser's Spiral
The Perception of Lightness
Apparent Lightness Illusion
Craik-O’Brien-Cornsweet Effect
Color Matching Is An Important Illusion That Is Understood Quantitatively
The Retina Has Three Layers And Five Basic Cell Types

Light absorption → Output to brain
There are Three Types of Cones Containing Different Photopigments

(Young, 1802)
A General Characterization of Cones By Color Matching
The Color Matching Experiment Is Linear

Test | Primaries
--- | ---
(a) | matches | + | + | \( t \) matches \( e \)
(b) | matches | + | + | \( t' \) matches \( e' \)
(c) | matches | + | + | \( t + t' \) matches \( e + e' \)
The Color Matching Experiment Is Linear

If

and

then

matches
The Color Matching Measurements are the CMFs (10 deg shown)
Color Matching Is Efficiently Summarized by 3 Linear Equations

\[
\begin{pmatrix}
    R \\
    G \\
    B
\end{pmatrix}
= 
\begin{pmatrix}
    CIE RGB functions
\end{pmatrix}
\begin{pmatrix}
    t
\end{pmatrix}
\]

\[r = R t\]
Color Matching Is Efficiently Summarized by 3 Linear Equations

(for people who prefer integrals to matrices)

\[ R = \int r(\lambda)t(\lambda) d\lambda \]
\[ G = \int g(\lambda)t(\lambda) d\lambda \]
\[ B = \int b(\lambda)t(\lambda) d\lambda \]
The Wavelength Response Selectivity of the Three Cone Types Has Been Measured
(Schnapf, Nunn, Baylor)
Cone Photocurrent Wavelength Sensitivity (Without The Optics)
Stimuli Causing Equal Cone Absorptions Match Perceptually

![Graphs and images of cone types L, M, S with absorption rates]
Cone Responsivity Predicts The CMFs Measured Behaviorally
(Schnapf, Nunn, Baylor)
The Matching Illusion Can Be Predicted From The CMFs or the Cones

\[
\begin{pmatrix}
R \\
G \\
B
\end{pmatrix}
= \begin{pmatrix}
\text{Red} \\
\text{Green} \\
\text{Blue}
\end{pmatrix}
\begin{pmatrix}
t \\
\end{pmatrix}
= \begin{pmatrix}
\text{Red} \\
\text{Green} \\
\text{Blue}
\end{pmatrix}
\begin{pmatrix}
t' \\
\end{pmatrix}
\]

\[r = \text{Rt} = \text{Rt'} \quad \text{-- t and t' are called metamers}\]
Matching Is Not The Same As Appearance

After Albers
Color Appearance Depends On The Spatial Pattern Across The Cone Mosaic (Shevell and Monnier)
To Understand Appearance, We Must Understand Image Formation And Spatial Encoding
Chromatic Aberration Of The Human Image Formation Has A Large Effect on Color
Chromatic Aberration is consistent across many labs and due to the water in the eye.
Chromatic Aberration Can Be Measured By Wavelength-Dependent Spread of The Linespread Function
Chromatic Aberration Influences Appearance
The Image Is Encoded by the Cones And Then Recoded for Transmission by the Retinal Pathways

Light enters

Ganglion On/Off

Bipolar Horizontal Amacrine

Photoreceptors

50 microns
The Similarity Of Spectral Tuning Makes Cone Signals Correlated (Buchsbaum)
Appearance And Sensitivity Measurements Show That Neural Signals Reduce the Correlation By Carrying The Difference Between Cone Signals (Hering, Hurvich and Jameson, Stiles, Boynton, Stromeyer, Wandell)
Colors Appear Red or Green, But Not Red AND Green; Blue or Yellow, But not Blue AND Yellow; They Can Appear Red and Yellow

Hypothesis: This appearance regularity arises from retinal encoding
Hue Cancellation Experiment
Measures Color Opponency Empirically
The Original Color Opponency Measurements Were Made by Hurvich and Jameson
Human Retina By The Numbers
(Rodieck, 1998)

- 5 x 5 cm, 0.4 mm thick
- # cones: $5 \times 10^6$
- # rods: $10^8$
- Cone width in fovea: 1 mu
- Contacts per cone: 250
- $10^6$ optic nerve fibers
Spatial Distribution of Receptors Is Very Uneven Across The Retina

(a) Left eye

(b) Receptors per square mm ($x 10^5$)

Angle relative to fovea (degrees)

-60  -40  -20  0   20   40   60

temporal  nasal

Blindspot

Rods
Cones
The Primate Foveal Retina Contains Mainly Cones And Is Specialized For High Acuity and Color
In The Fovea, The Cones Are Tightly Packed And Small; The Cones Are Larger and Interspersed With Rods in the Periphery (Curcio et al., 1990)
S-Cones Represent 7% (1/14) Of All Cones
Retinal Cell Types Can Be Distinguished By Their Size And Branching Patterns (Dacey, 1993; Rodieck 1998)
Cell Size Within A Class Usually Increases With Eccentricity
(Dacey, 1993; Rodieck, 1998)

![Graph showing dendritic field diameter vs retinal eccentricity with Parasol, Small bistratified, and Midget cells highlighted.](image-url)
Multiple Retinal Pathways Exist, Having Very Specific Spatial Patterns of Cone Connections
(Rodieck, 1998)
The Retina Contains A Specialized Rod Pathway
(Macaque, rod pathway; Massey in Rodieck Book)

Rod bipolar

AII amacrines
There Is Highly Specialized S-Cone Circuitry

(Calkins, J. Del Valle, Kouyama and Marshak, 1992)

*S-cone bipolars receive exclusively from *S*-cones and are pre-synaptic to the small bi-stratified retinal ganglion cells

*Identified using an antibody for the neuropeptide cholecystokinin (CCK)*
A Major Retinal Output For S-cone Signals Is the Mosaic of Small Bi-stratified Ganglion Cells

(Calkins)

(Calkins and Sterling)
Hypothesis:
The Spatial Organization of the Cone Inputs To The Retinal Pathways Are The Origin of Perceptual Color Opponency
(DeValois, 1959, 1964; Hubel and Wiesel, 1966; Calkins and Sterling, 2001)
A Sweep Frequency Conveniently Illustrates The Measurement of Spatial Contrast Sensitivity
The Ability To See Color Varies With The Stimulus S-T
(D. H. Kelly, 1979)
Trichromacy is Restricted To A Subset of the Visible Spatial Temporal Regime

Limiting factors:
Chromatic aberration
Retinal encoding
Other factors?
Poor Spatial Resolution For Color Is the Basis for Compression in NTSC and JPEG
Blurred Y

Blurred I

Blurred Q

Blurred Y
Blurred I
Blurred Q

Blurred Y, Q
Blurred I, Y, Q
Blurred Q, Y, I

Blurred Y
Blurred I
Blurred Q

Blurred Y
Blurred I
Blurred Q
Color Opponency Is Implicit In Color Metric Standards
Spatial and Temporal Variations In Color Sensitivity Are Significant

<table>
<thead>
<tr>
<th>Reduced luminance contrast</th>
<th>Original</th>
<th>Reduced blue-yellow contrast</th>
</tr>
</thead>
</table>
Color Appearance Degradation Can Be Measured Using Asymmetric Color Matching
(Poirson and Wandell, 1993)

Poirson and Wandell,
Spatial CIELAB Is A First Attempt To Extend Color Metrics
(Zhang and Wandell)

- Backward compatibility
  - Gives identical result as standard CIELAB when input is uniform area.
- Modular design
  - Easy to upgrade to newer CIELAB standard such as CIE94.
- Spatial filtering on linear opponent representations
  - Filtering occurs before CIELAB calculations, because linear filtering should be performed on linear representation
- Pattern-color separable spatial filtering
  - Not the same as spatial filtering in other color spaces such as L*a*b*, YIQ, YCbCr.

http://white.stanford.edu/~brian/scielab/scielab.html
Retinal Ganglion Cells Project In An Organized Fashion to The Lateral Geniculate Nucleus; Signals Are Then Sent To Primary Visual Cortex
The Lateral Geniculate Nucleus Layers Receive Inputs From Different Ganglion Cell Types; The Responses in These Layers Mirror The Retinal Organization; The LGN Signals Are Transmitted to Distinct Cortical Layers
Human Brain By The Numbers
(Braitenberg and Schutz, 1991)

Neurons are the computational elements
White matter connects the neurons via axons
The connection is called the synapse

- Neurons: $10^{11}$
- Synapses: $10^{14}$
- Synapses/neuron $10^3$
- Surface area of each hemisphere: $25 \times 30$ cm$^2$
- Most connections are local (10-100 um); some span many cm
- Neurons/mm$^3$: $10^4$-$10^6$
- Axon length/mm$^3$: 3 km
Magnetic Resonance Scanners Can Be Used To Measure Brain Activity
(Wandell, 1999)

Functional MRI

- Non-invasive
- Measures intrinsic signal (dipole relaxation)
- Spatial resolution ~ 2 mm
- Temporal resolution ~ 5 sec
- Can study individual subjects in detail
The fMRI Signal Is Based On Measurements Of Hydrogen Atoms Bound to Water

T2 Relaxation
There Is An Increase In Oxygenated Blood Flow To Active Regions of Cortex  
J.F. Fulton, M.D. (1928)

- Subject noted that ‘the noise in the back of his head increased in intensity when he was using his eyes.’
- No increase for hearing, touch or smell
- Increased more when he tried harder
The fMRI Signal Measures Blood Oxygenation

Control state

Arterial

Venous

Active state

Arterial

Venous

OEF: 0.4

OEF: 0.4/1.2

Heart lung

Heart lung

Brain

Brain
Cortex Contains Multiple Visual Maps That Can Be Measured Using fMRI in Human and Macaque

(Brewer, Press, Logothetis, Wandell)
Color Responsivity in V1 Is Similar To Behavioral Sensitivity
(Engel, Zhang, Wandell, 1997)
Color Responses Exceed Achromatic Responses Primarily In Ventral Occipital Cortex (Wade, Brewer, Rieger, Wandell, 2002)
Human Ventral Occipital Cortex, Near hV4, Responds Powerfully to Color Signals; Damage Can Cause A Hemifield Loss of Color Perception
Variations in Illumination Change The Light Scattered To Our Eyes From An Object

Courtesy S. Tominaga
Color Appearance is Calculated Across Space
Demonstration of Adaptation
It is desirable to associate color appearance with the surface scattering, not the reflected light.

Illuminant 1

Appearance

Color balancing solutions
Two components.
1. Make an estimate of the spectral composition of the illumination.
2. Use a method to transform the acquired data into appropriate display values.
If Color Balancing Fails, The Appearance Can Be Very Wrong
Best Information About the Illumination Is In Light Regions
Various Methods Have Been Used To Measure Adaptation In People

Chichilnisky and Wandell

Kraft and Brainard

He, Makous, MacLeod
Bauml
Fairchild and Berns
Delahunt and Brainard
... Many others
Dichoptic Color Matching Data Support A Simple Gain Control Model As a 1st Approximation

The Gain Control Model Is Also Called von Kries Adaptation And Can Be Expressed In Simple Mathematical Form

\[
\begin{pmatrix}
\Delta L' \\
\Delta M' \\
\Delta S'
\end{pmatrix} =
\begin{pmatrix}
G_L(T, M) & 0 & 0 \\
0 & G_M(T, M) & 0 \\
0 & 0 & G_S(T, M)
\end{pmatrix}
\begin{pmatrix}
\Delta L \\
\Delta M \\
\Delta S
\end{pmatrix}
\]

Where \( G \) is the receptor gain. Its value depends on the properties of the Test and Match contexts.
Von Kries Adaptation Still Leaves Unanswered Questions About How The Gain Is Set

What determines the scale factors?
It Is Possible To Measure Color Sensitivity Changes In Human Cortex
(Wade and Wandell, 2002)
An FMRI Paradigm Used To Measure Gain Control

Block design

- Test Probe:
  - Low contrast dartboard
  - Flickering at 2Hz
  - Constant amplitude (small)
  - S-cone or L,M-cone probes

- Background
  - Large (30 deg diameter)
  - Changing very slowly
  - S-cone or L,M-cone change
Changes In Sensitivity Can Be Measured in the fMRI Time Series And Compared With Behavior
Tutorial Outline

• Introduction: Appearance and Computation
• Wavelength encoding and the photoreceptors
• Spatiotemporal sensitivity and the retina
• Color coding and visual cortex
• Visual Adaptation
Suggested Readings and Reference Volumes

Vision Science
Foundations of Vision (B. A. Wandell)
The First Steps in Seeing (R.W. Rodieck)
A Vision of the Brain (S. Zeki)
Eye, Brain and Vision (D. Hubel)
Color vision : from genes to perception (Ed. Gegenfurtner and Sharpe)

Color Science and Engineering
Color science : concepts and methods, quantitative data and formulae (Wyszecki and Stiles)
Color in business, science, and industry (Deane B.Judd and Guenter Wyszecki)
Principles of Color Technology (Berns, Billmeyer and Saltzman)
Reproduction of Colour (R.W.G. Hunt)

Perception
Goldstein’s Sensation and Perception

Neuroscience
The astonishing hypothesis : the scientific search for the soul (Francis Crick)
The New cognitive neurosciences (Ed. Michael S. Gazzaniga)
The Human Components of Image Systems

Brian Wandell
Psychology and EE
Stanford University

Web-sites
www.imageval.com
www.vischeck.com
white.stanford.edu

Many of the images in this tutorial are from
Wandell, Foundations of Vision, Sinauer Press