COMP 546

Lecture 3

Color, Photoreceptors

Tues. Jan. 17, 2017
Spectrum

400 nm

700 nm

\(\lambda\)
Types of Spectra

- Emission
- Surface Reflectance (fraction)
- Absorption by photoreceptors (fraction)
Emission (light source)
Reflectance

Fraction of light (at each wavelength) reflected from a surface

Six samples (and model fit) from standard MacBeth Color Chart.
I’m not sure which six squares these plots correspond to.
Absorption (photoreceptors)
Photoreceptors: Rods and Cones

Rods → Cones
Rods

• Night vision
• Black and white
• Peripheral vision
• Low acuity

Cones

• Day vision
• Color
• Central vision
• High acuity (in center)
Rods and cones: light levels

[Diagram showing the relationship between luminance levels and vision regimes: Scotopic vision regime, Mesopic vision regime, Photopic vision regime, Cone-mediated vision, Rod-mediated vision.]

- No moon (overcast)
- Moonlight (Full moon)
- Early twilight
- Store or office
- Outdoors (sunny)

Luminance (cd/m²): $10^{-6}$ to $10^6$
Spectral ‘sensitivity’ of rods

Fraction of light of wavelength $\lambda$ that will be absorbed by rod pigment. (For illustration purposes, the curve is normalized to 1.)
Spectral ‘sensitivity’ of cones

Fraction of light of wavelength $\lambda$, absorbed by each type of photoreceptor pigment. (For illustration purposes, each curve is normalized to 1.)
There are far more L (red) and M (green) cones than S (blue).

Why? Chromatic aberration (see lecture notes).
Principle of Univariance

Once a photon of some wavelength is absorbed ("caught") by the photoreceptor, information about wavelength is gone.

How to express this mathematically? We consider only the cones.
$E(x, \lambda)$ - spectrum of light arriving at cone $x$

$C_{LMS}(\lambda)$ - spectral sensitivity of a photoreceptor (either L, M, or S)

$$I_{LMS}(x) = \int C_{LMS}(\lambda) \ E(x, \lambda) \ d\lambda$$
The photoreceptor “response” is some unspecified function of \( I_{LMS}(x) \).
Metamers

It can easily happen that two spectra are mapped to the same LMS triplet, i.e.

\[ C_{LMS} \ E_1 = C_{LMS} \ E_2 \]

Such spectra are visually indistinguishable, and are called 'metamers". 
Three basic types of color blindness depend on which cone photopigment is missing.
(Color blind people have more metamers.)
Normal

Color blind
(e.g. missing L cones)
Rod (night) vision is an extreme case of metamerism
RGB images (and displays)
Color displays

When properly drawn, peaks correspond to $P$ matrix on right.

Monitor, projector spectra

$E_{RGB}(x)$ $=$ $P_{RGB}$

RGB in $[0,1]$
\[ I_{LMS}(x) \quad = \quad C_{LMS}(\lambda) \quad \Rightarrow \quad P_{RGB} \]

- \( I_{LMS}(x) \): Input \( x \times 1 \) pixel values.
- \( C_{LMS}(\lambda) \): \( N \times 3 \) cone absorptance spectra.
- \( P_{RGB} \): \( 3 \times 1 \) RGB values in \([0,1]\).

3 x 3 transform from pixel values to cone absorptance.

Monitor, projector spectra.
Color display gamut
(bounds on cone response triplets)

\[ I_{LMS}(x) \]
Types of Spectra

- Emission
- Surface Reflectance (fraction)
- Absorption by photoreceptors (fraction)
- Transmission (fraction)
Anaglyph (definition): a photograph with the two images superimposed and printed in different colors, producing a 3D effect when viewed through correspondingly colored filters.
Anaglyph: left and right eye

- Black: (0,0,0)
- White: (1,1,1)
- Cyan: (0,1,1)
- Red: (1,0,0)
Today’s remaining topics

• Phototransduction
• Temporal aspects: adaptation
• Spatial aspects: density
Phototransduction

Light is absorbed by a pigment in photoreceptor cell.

This leads to opening and closing of ion channels (Ca, Na, K), causing changes in electrical potential across cell membrane. *One can measure difference in electrical potential across membrane using tiny electrodes.*

Varying ion concentrations cause cell to release varying amounts of neurotransmitters (hormone) which binds to neighbor cell, *and which signal the changes in intensity of light absorbed.*
Photoreceptor response to a light flash is a change in voltage across the cell membrane. The time scale in the plot below is rather long.
Adaptation
Time Scales

- fraction of a second
  scanning a “high dynamic range” scene (e.g. containing shadows on dark colored surfaces + illuminated regions on white surfaces)

- seconds
  previous slide

- minutes
  light adaptation: rods to cones
  dark adaptation: cones to rods
ASIDE: Pupil Response

Another form of adaptation: partly compensates for changes in average light level over the whole image.

Diameter of pupil ~2 - 8 mm.

This is only a small contribution to huge operating range of the visual system.
**FIGURE 3-7**  The distribution of rods and cones in the human retina. The left figure gives the locations on the retina of the “angle” relative to the optic axis on the right figure (based on Lindsay & Norman, 1977).

ML:  This is the left eye
Hold two fingers in front of you at arms length. Close your left eye. Move your right finger away until the fingernail disappears (about 15 degrees)
\[
\frac{1 \text{ mm}}{20 \text{ mm}} \times \frac{180 \text{ degrees}}{\pi \text{ radian}} \approx 3 \text{ degrees}
\]

See Exercises for foveal vs. peripheral sampling density (per deg)
Acuity

How many lines per degree can you see (before image starts to look gray)?

Limited by optics (blur, and aberrations) and photoreceptor sampling, ...
Acuity is worse in the periphery

Again, ... limited by optics and photoreceptor sampling, ...
Next lecture: the Retina

light

pigment epithelium
photoreceptors
horizontal cells
outer synaptic layer
bipolar cells
amacrine cells
inner synaptic layer
ganglion cells
optic nerve fibre
optic nerve

signals

To the brain