A high frequency, full-spectrum review of color vision concepts

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Goals

- A lot to cover in one hour
- Hope to impart the basics, especially abstract concepts to help frame study
- I'll mostly summarize the theoretical background, and help orient on graphs.

References

- Dr. Verdon's VS205 slides (2007-2010)
- Dr. Haegerstrom-Portnoy's VS212E slides (2010)
- Schwartz Chapter 5 and 6
- Verdon and Adams chapter of Norton, et al. book
- Webvision `http://webvision.med.utah.edu/KallColor.html`
- Dr. Salmon's (Northeastern) VS2 notes `http://arapaho.nsuok.edu/~salmonto/vs2.html`
- HyperPhysics Color Vision Concepts `http://hyperphysics.phy-astr.gsu.edu/hbase/vision/colviscon.html`
- handprint : color vision `http://handprint.com/LS/CVS/color.html`

Outline from NBEO

OPTICS (PHYSIOLOGICAL): Perceptual Function / Color Vision

G. Color Perception

1. Chromatic discrimination (hue and saturation) for normal and defective
2. Color mixture and appearance
3. Color contrast, constancy, and adaptation
4. Color specification and colorimetry (CIE)
5. Spectral sensitivity of normal and defective color vision
6. Mechanisms of color deficiencies
7. Inherited anomalies of color vision
    a. Classification
    b. Inheritance patterns
    c. Color vision tests (e.g., pseudoisochromatic tests, arrangement tests
8. Acquired anomalies of color vision
    a. Classification
    b. Etiology
    c. Color vision tests
9. Conditions for color vision testing
10. Societal implications of color vision anomalies
    a. School
    b. Vocational requirements
    c. Patient interest
11. Patient management strategies
    a. Counseling
    b. Special aids

Example questions from NBEO

Sample Test Items
Part I (Applied Basic Science)

1. The portion of the spectrum called blue-green by normals is MOST readily confused with the white portion for which of the following types of observers?
    a. Trichromats
    b. Deuteranopes
    c. Tritanopes

Classification: Optics (Physical): Perceptual Anomalies / Color Vision; Explicit

2. Both a husband and wife pass standard color vision tests. If the wife’s father has an inherited red-green color defect, what is the probability that the couple’s daughter will be color defective?
    a. 0.00
    b. 0.25
    c. 0.50
    d. 1.00

Classification: Optics (Physiological): Perceptual Anomalies / Color Vision; Explicit

Outline

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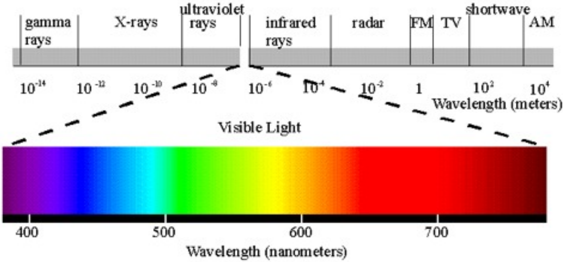
Basic terms

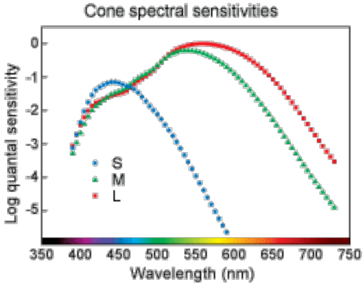
- *Color vision:* the ability to **discriminate** stimuli based on wavelengths of light
- *Metamers:* stimuli that appear the same but are physically different
- *"Making a match":* ability to make two stimuli metameric, often indicates a defect.
- *Spectral composition:* a light source is made up of amounts of light at one or many wavelengths (i.e., sunlight)
- *Monochromatic light:* light source made up of a single wavelength. (i.e., laser).

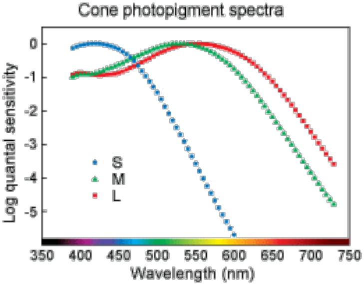
Visible lights

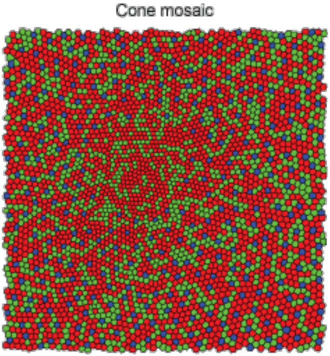
- lower (UV) limited: Media, esp. lens
- upper (IR) limited: insensitivity



3 cone types



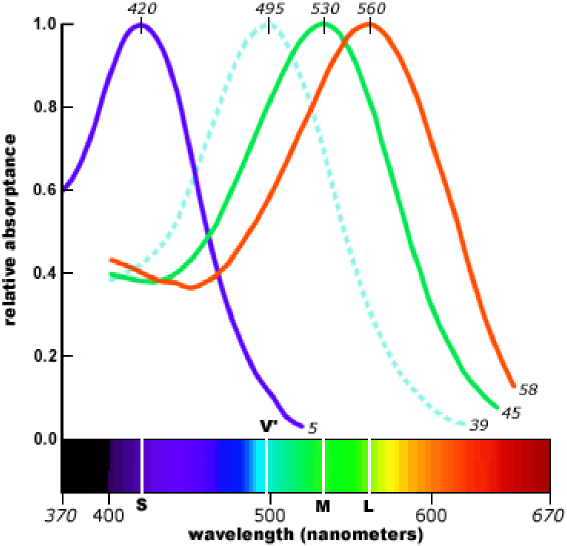




CVRL

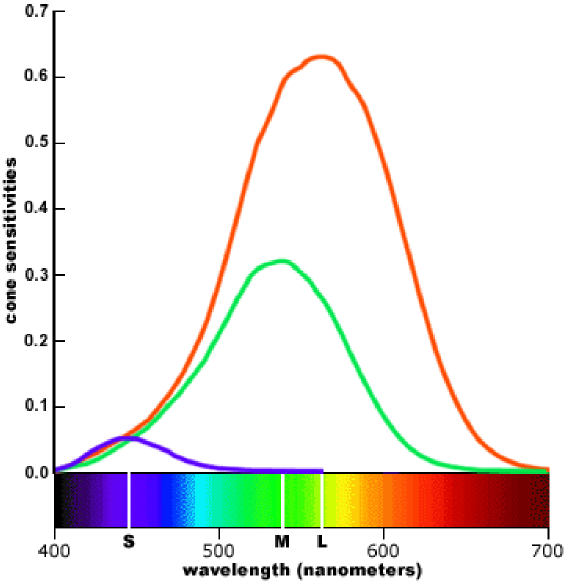
3 photopigments

- Color normals are "trichromatic"
- S/cyanolabe: 420, M/chlorolabe:530, L/erythrolabe:560
- Rods not involved



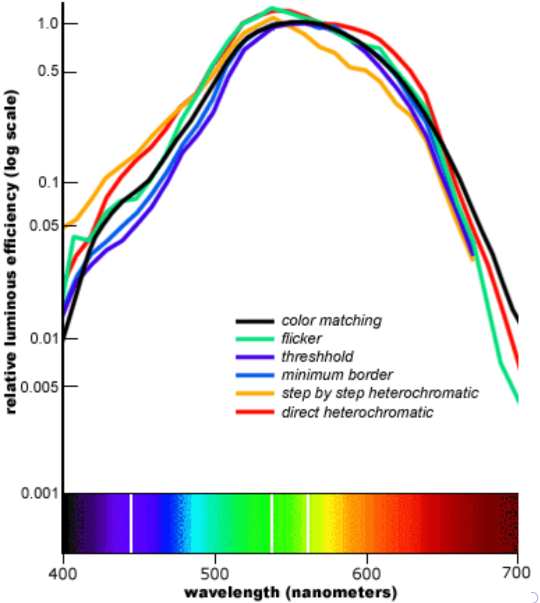
The “real” sensitivies

- Actual sensitivity to wavelengths depends on population of S,M,L cones
- L:M:S=32:16:1
- Remember no S cones in the central fovea! *(Near-field tritanopia.)*



Overall (combined) spectral sensitivity

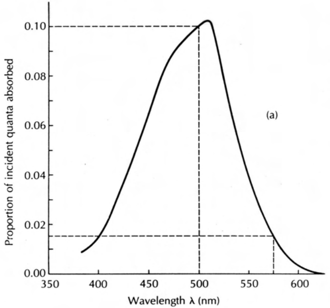
- Known as $V(\lambda)$
- Curves represent different measurement methods
- Photopic vision peaks around 555nm

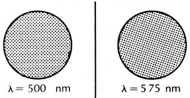


Outline

Monochromat

- Monochromats: only one pigment (could be rods)
- Due to Principle/Univ.: One single "color" with varying brightness
- Think B&W TV!





Quanta incident	Quanta absorbed	Quanta incident	Quanta absorbed
1000	100	1000	15
1000	100	6667	100
2000	200	13,334	200

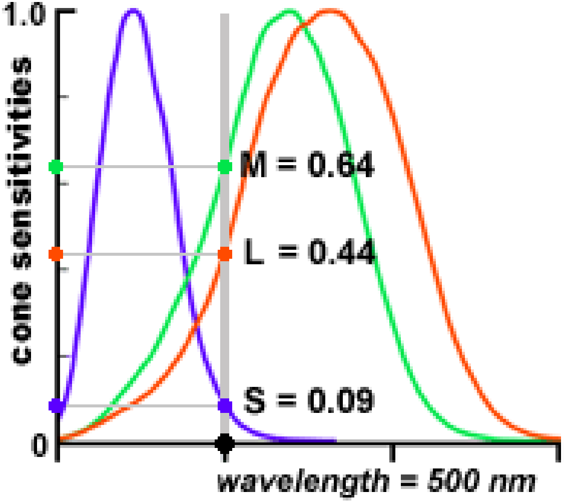
(b)

Fig. 8.2 **(a) The absorption spectrum of rhodopsin. This curve has an unfamiliar shape because the scale on the vertical axis is linear, instead of the usual logarithmic one. The linear scale is used here to simplify the numerical illustrations in the text. (The data plotted here are identical with those plotted the more usual way in Fig. 5.6.) (b) When two patches of light are flashed, one of wavelength 500 and the other 575 nm, the table indicates the numbers of quanta absorbed by rhodopsin from each patch.**

Monochromacy Demo

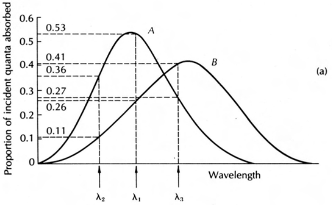
Combination of cone responses used

- Color discrimination is based on combination of cone responses
- **Principle of univariance:** cones “forget” what wavelength they absorbed



Dichromat metamer

- Dichromats: missing one pigment
- Reduces their ability to discriminate *based on wavelength alone*
- 3 lights can be combined to appear metameric
- Trichromatic would **never** match!



Wave-length	Quanta incident	Quanta absorbed by *A*	Quanta absorbed by *B*	Quanta incident	Quanta absorbed by *A*	Quanta absorbed by *B*
			Condition 1			
λ_1	1000	530	260	0	0	0
λ_2	0	0	0	1000	360	110
λ_3	0	0	0	1000	270	410
Total effect:		530	260		630	520
			Condition 2			
λ_1	1000	530*	260	0	0	0
λ_2	0	0	0	1250	450	137
λ_3	0	0	0	300	80	123
Total effect:		530	260		530	260

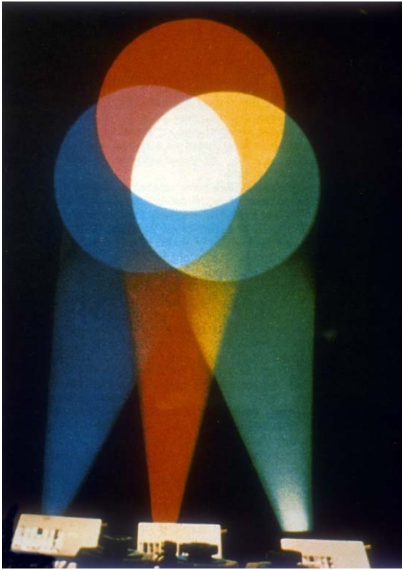
(b)

Fig. 8.7 **(a) Absorption spectra for two hypothetical visual pigments, and (b) the corresponding effects of lights upon a visual system containing only those two pigments. It is always possible to find intensities for λ_2 and λ_3 such that the effects of their mixture (the right-hand patch) will be identical to the effects of λ_1 (left-hand patch).**

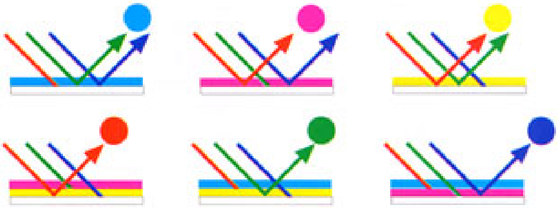
Outline

Additive color mixtures

- We generally consider additive color mixtures
- vs. subtractive (like paint/pigment which absorbs wavelengths)
- Filters “pass” their associated color
- Helpful: lowpass, bandpass, highpass for colored filter



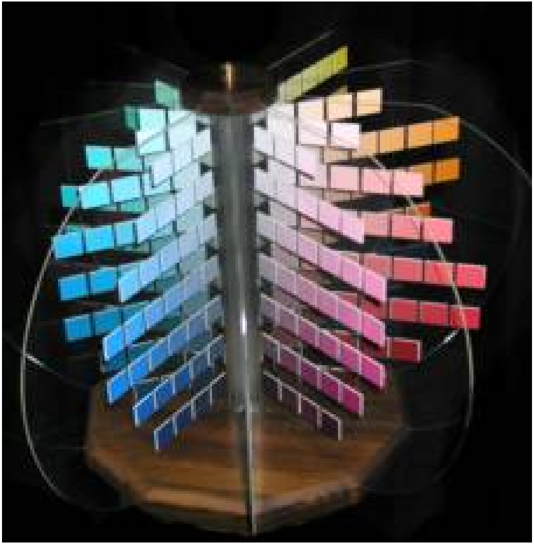
Subtractive: Color depends on illuminant and surface



Ink Color	Absorbs	Reflects	Appears
C	Red light	Green and Blue light	Cyan
M	Green light	Red and Blue light	Magenta
Y	Blue light	Red and Green light	Yellow
M + Y	Green & Blue light	Red light	Red
C + Y	Red and Blue light	Green light	Green
C + M	Red and Green light	Blue light	Blue

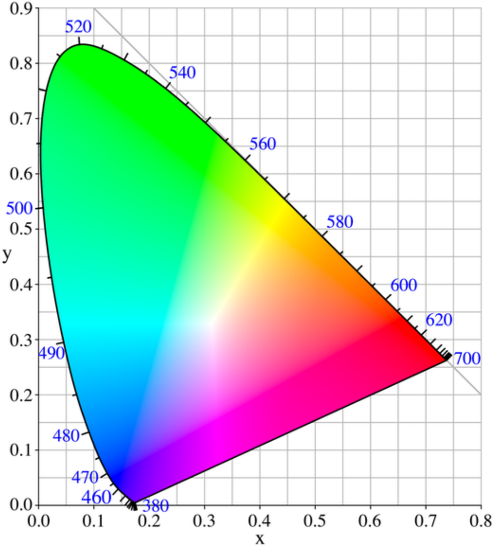
Color appearance terms (perceptual)

- **Hue**: Color, Dominant wavelength
- (De)**Saturation/ purity**: Appearance of added white. Munsell: *Chroma*, left-right
- **Brightness**: Luminosity, Intensity, Munsell: *Value*, up-down
- Are not strictly independent: Bezold-Brucke, Abney effect



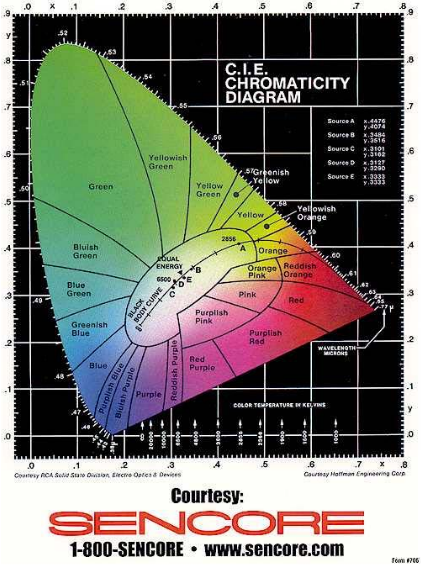
CIE Chromaticity Diagram

- Color appearence: *perceptual*
- Brightness not shown (only hue+saturation, aka “chromaticity”)
- Hues radiate to spectral locus
- White is in center
- Color mixtures lie *between* two colors



CIE Chromaticity Diagram

- The standard coordinate system based on 3 “imaginary” primaries
- Spectral locus
- Non-spectral purple
- Blackbody curve (Planckian locus)
- Whites near center



Excitation purity

- D = Dominant wavelength
- Exc. purity = $\frac{a}{a+b}$
- 0 = white
- 1 = spectral locus

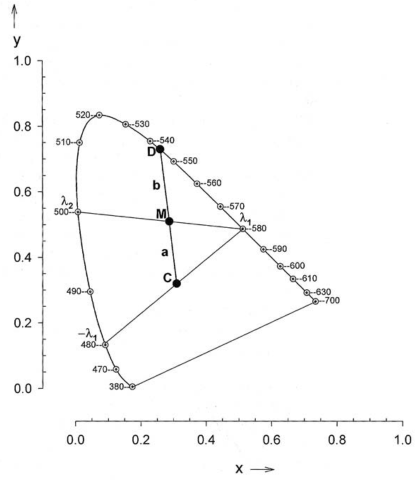
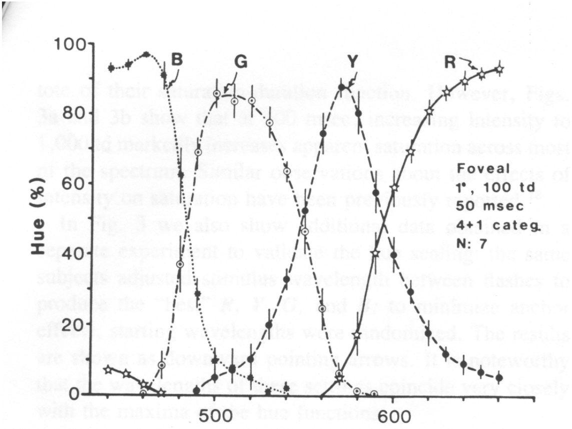


FIGURE 8.9 *The CIE 1931 (x, y) chromaticity diagram on which are shown the locations of points, distances, and directions that can be used to determine the dominant wavelength (D) and the excitation purity (a/[a+b]) for a color mixture (M) created by mixing the appropriate amounts of two wavelengths (λ_1 and λ_2). It also shows two complementary colors (λ_1 and $-\lambda_1$). See text for details. C is the location of the reference white. (Modified from G Wyszecki, WS Stiles. Color Science: Concepts and Methods, Quantitative Data and Formulae [2nd ed]. New York: Wiley, 1982.)*

Outline

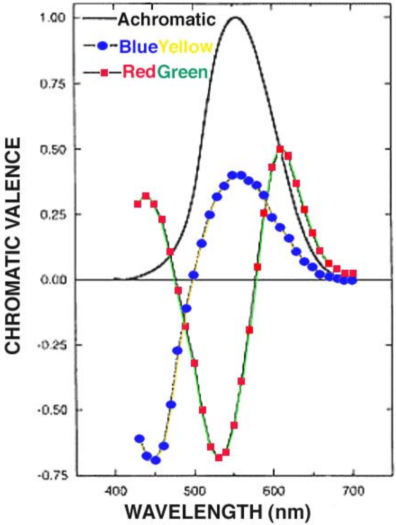
Color opponency

- Subjects can **name** all colors based on (B vs. Y) and (R vs. G)
- Unique hues when 0% of opposite channel
- Two diagonal axes on CIE diagram



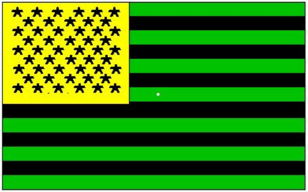
Chromatic valence

- Experiment asked subjects to add B/Y or R/G to target wavelength to make it white
- On this graph, zero-crossings are unique hues (of other channel)



Chromatic adaptation

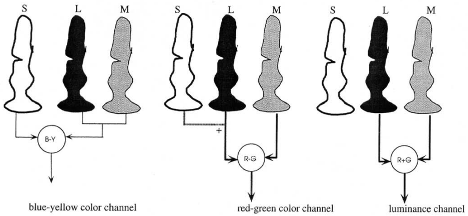
- Chromatic adaptation: Neurons “tire” to repeated presentation
- Chromatic adaptation best understood as shift towards opponent color in pathway



Chromatic adaptation

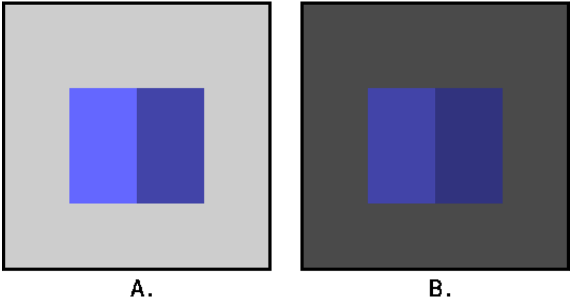
Zone model

- Unifying opponency and trichromacy
- B/Y, R/G, and achromatic luminance channel
- Opponency originates in the latest stages of the retina, specifically (P/midget vs. bistratified ganglion cells–parvo vs. konio pathway)



Color constancy

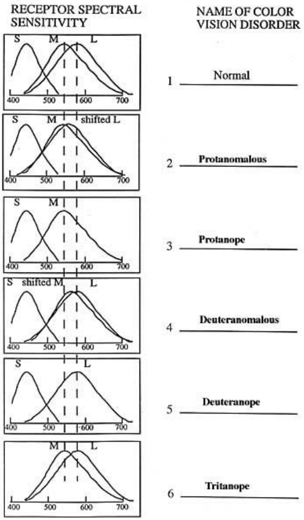
- (High-level) perception of color is modulated by context
- Right side of A is same as left side of B
- Also: why objects look the same under different illumination



Outline

Common inherited CVDs

- Protan: L cone.
  Missing, or shifts left
- Deutan: M cone.
  Missing, or shifts right
- vs:
- Tritan: S cone.
  Missing (rare)
- Dotted lines show “normal” pigments



CVD summary

Hereditary	Acquired
predominantly R/G	B/Y or R/G
predominantly male	M or F
no naming errors	recent errors
stable	variable or progressive
clear-cut	difficult to diagnose
no disease	disease
binocular	monocular or asymmetric

CVD summary: Kollner's rule

Kollners Rule: Lesions at the level of the receptor layers, or in the pre-retinal media are more commonly associated with blue-yellow (better termed tritan) disorders of color vision. Lesions in the post receptoral layers (inner retina, ganglion cells & visual pathways) are more likely to exhibit red-green color disorders.

	Blue-yellow defects	Red-green defects
Kollner's rule	media, choroid, outer retina	optic nerve, inner retina
Examples	cataract, diabetes, RD, macular degeneration, chorioretinitis, central serious retinopathy	optic neuritis, papillitis, Leber's, central optic atrophy, toxic amblyopia, visual pathway lesions
Exceptions	glaucoma, papilledema	dominant cystoid macular dystrophy, Strargardt's disease (fundus flavimaculatus)

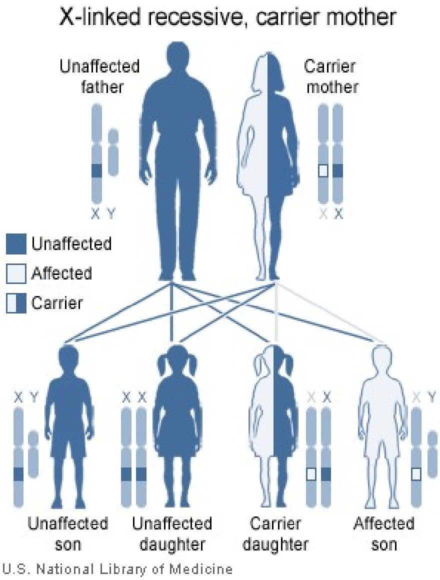
Outline

Inherited color vision defects

Deuteranomaly	5%(males)	X-L recessive
Deuteranopia	1%(males)	X-L recessive
Protanomaly	1%(males)	X-L recessive
Protanopia	1%(males)	X-L recessive
Tritanomaly and tritanopia	0.001-0.007%	AD (or acquired
Rod monochromacy	0.003%	AR
Blue cone monochromacy	???rare	X-L recessive
Cone monochromacy	???extremely rare???	

Study the inheritence patterns & Punnett squares!
See
`http://en.wikipedia.org/wiki/Color_blindness`

Inheritance example from Wikipedia



Example questions from NBEO

Sample Test Items
Part I (Applied Basic Science)

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   a. 0.00
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   d. 1.00

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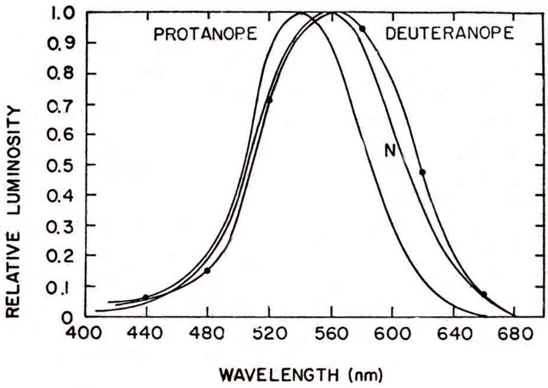
Outline

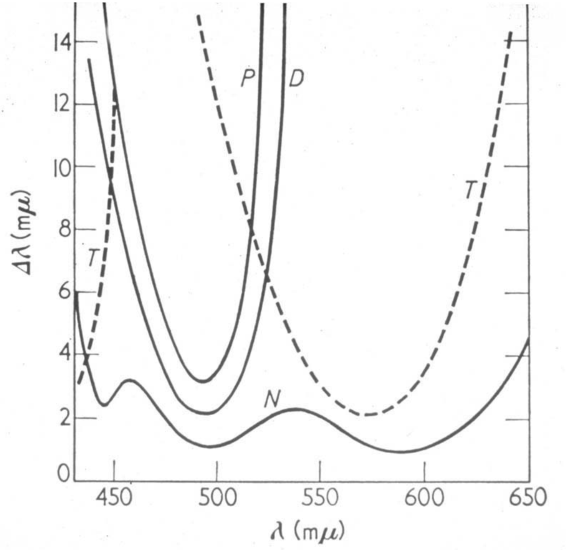
Altered V(λ) curves

- Tritans normal
- Deuteranope almost normal
- Protanope quite different (due to prevalence of missing L cones)
- "Dimming of the red"



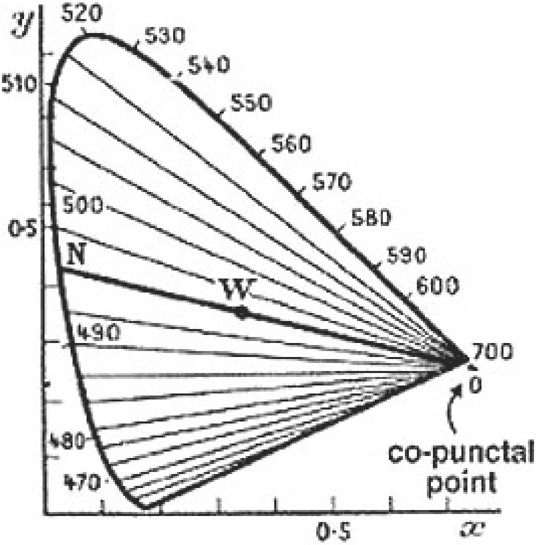
Wavelength discrimination

- Normals have down to 1nm discrimination capability near 490 and 590
- Protanopes and deuteranopes only discriminate well between 450&540
- Tritanopes have a gap with no discrimination between 460&480



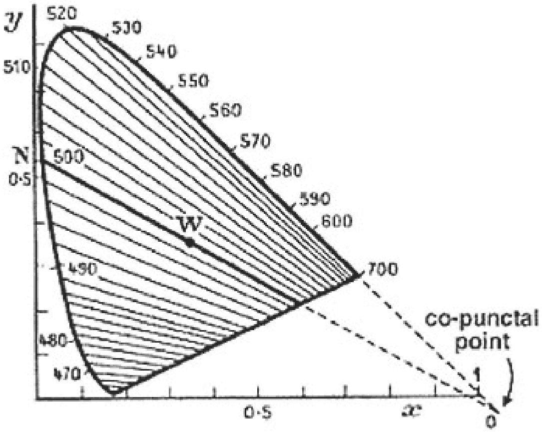
Protanope confusion lines

- Dichromats have *copunctal points* and *confusion lines*
- They cannot distinguish colors on a given confusion line
- Intersection w/spectral locus through white is called "neutral point" (N)

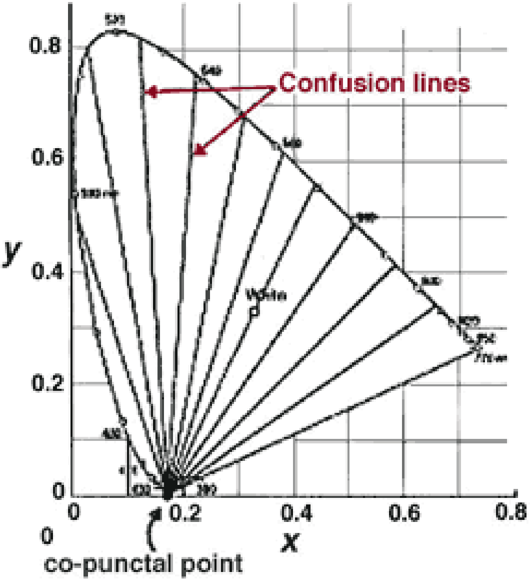


Deuteranope confusion lines

- Deuteranopes and protanopes share confusion line along spectral locus



Tritanope confusion lines



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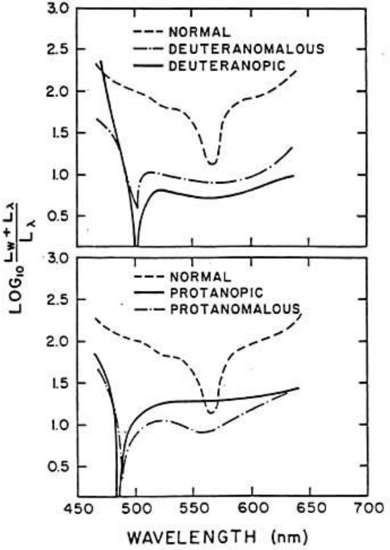
Saturation discrimination

- For normals, yellow is hardest to distinguish from white
- Only dichromats have neutral points (wavelength indistinguishable from white)



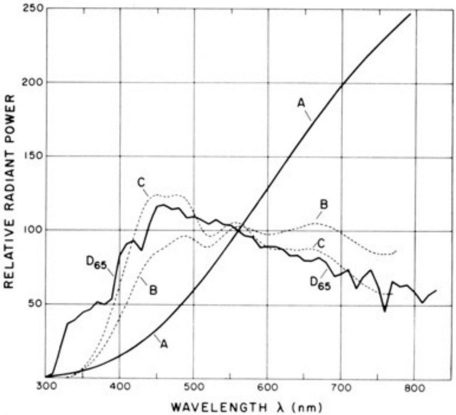
Color vision aids

- Red goggles for achromatic photophobia
- Colored filter for R/G CVDs can help with vocation. (Filter may allow patient to discriminate based on luminance difference induced by filter).

Outline

Testing conditions & standard illuminants

- Standard illuminants: Spectral distribution is critical!
- Reflected color depends on illuminant and plate
- Must use Illum. C or incandescent bulb w/blue filter



3.3.4). Relative spectral radiant power distributions of CIE illuminants A, B, C,

CVT summary

- Ishihara Plates: Sensitive, R/G
- HRR Plates: Sensitive, R/G and B/Y
- D-15/F-100: Insensitive, R/G and B/Y
- Anomaloscope: Sensitive, R/G
- “Red cap test”: quick check with tropicamide cap: binocular, central/periph., monocular nasal/temp.

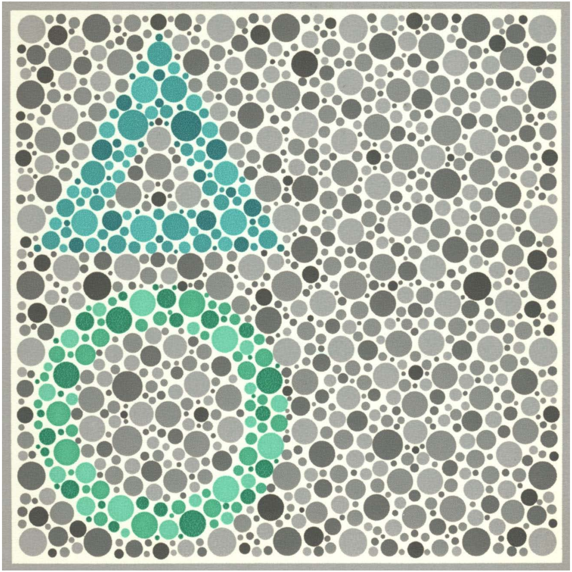
Outline

Types of plates: Ishihara

- **Transformation plates:** individuals with color vision defect should see a different figure from individuals with normal color vision.
- **Vanishing plates:** only individuals with normal color vision could recognize the figure.
- **Hidden digit plates:** only individuals with color vision defect could recognize the figure.

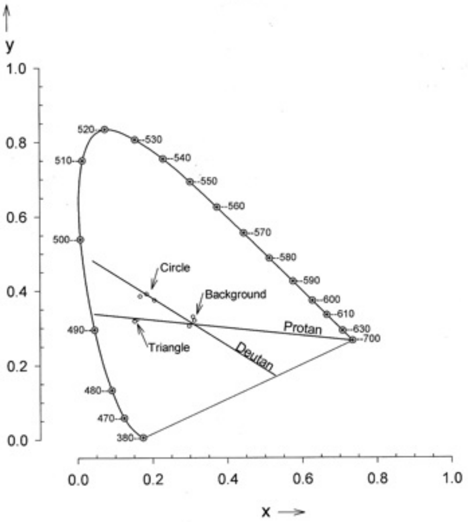
HRR diagnostic plate

- Circle or triangle indicates type of red/green defect



HRR diagnostic plate design

- See previous slide.
- If figure "matches" background color (on confusion line) it disappears for color defective



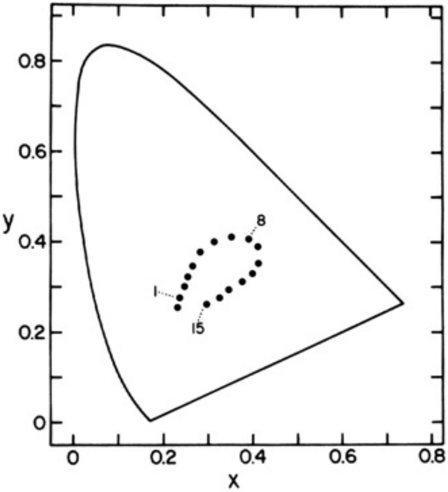
Ishihara hidden digit plate

- Hidden digit "appears" for CVD
- All types of plates (transformation, hidden digit, vanishing, diagnostic) use principle of confusion lines

Outline

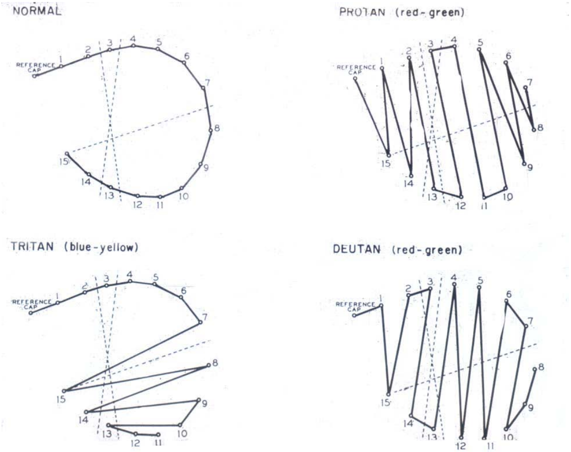
Farnsworth D-15

- Patient tries to arrange caps in order
- Caps are on ring in CIE which spans confusion lines to yield diagnostic error patterns

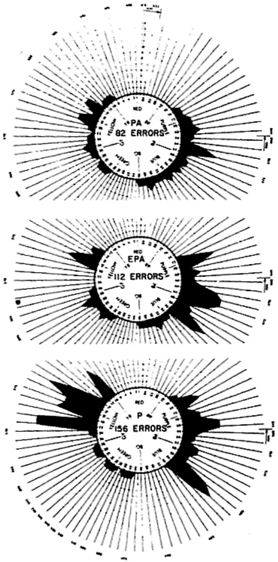


Location of Farnsworth D-15 caps in CIE color space

Farnsworth D-15 diagnosticity



FM 100 scoring



Outline

Neitz Anomaloscope

- Top: mixture of 545nm and 670nm (green/red) 0-73
- Bottom: test color at 589nm (yellow) brightness 0-35
- Can adjust mixture of top and luminance of bottom
- Rayleigh equation: "R+G=Y"

Anomaloscope diagnosticity

- Versus “normal” match. Mixture about 45, luminance about 17.
- Deureranopes: any mixture, same (normal) intensity
- Protanopes: any mixture, shifted intensity:
  - if top red, brightness low to match
  - if top green, brightness higher than normal
- Deuteranomalous: needs to add green. mixture is variable. brightness normal
- Protanomalous: needs to add red. mixture variable. brightness lower

Example questions (via Dr. Salmon)

Example question from the Optometry Exam Review Book:
Question #2. A color-deficient person looks in an anomaloscope and does not accept a color-normal's match? The nature of the person's deficiency is:

a. protanomaly
b. deuteranopia
c. protanopia
d. tritanopia

11. A patient mixes monochromatic green and red lights to obtain a metameric match with monochromatic yellow. If the he thinks any red-green mixture looks the same hue as the yellow light, which of the following diagnoses is/are possible?

a. protanomaly
b. protanopia
c. deuteranomaly
d. deuteranopia
e. none of the above

12. In addition to the adjustment described in Question 11, assume that the patient reduces the radiance of the yellow light below normal when the mixture setting is pure red, and increases the radiance above normal when the mixture is set to pure green. Which of the following diagnoses is/are possible?

a. protanomaly
b. protanopia
c. deuteranomaly
d. deuteranopia
e. none of the above

Example questions 2 (via Dr. Salmon)

13. For which of the following anomalies would the patient accept normal mixture and luminance settings?
a. protanomaly
b. protanopia
c. deuteranomaly
d. deuteranopia
e. none of the above

14. Suppose the mixture setting contains a slightly greater-than-normal amount of green but the luminance setting is normal. He probably has ..
a. protanomaly
b. protanopia
c. deuteranomaly
d. deuteranopia
e. none of the above

15. Suppose the mixture setting contains a slightly greater-than-normal amount of red but the luminance setting is significantly greater than normal. He probably has ..
a. deuteranomaly
b. deuteranopia
c. protanomaly
d. protanopia
e. none of the above

Anomaloscope Answers 1

2: (A) Protanomaly. (B) and (C) are R/G dichromats, which means they are missing a photopigment and CANNOT discriminate the colors on the anomaloscope. So they accept all matches, including the normal's. Tritanopia (D) is a B/Y defect, so they should perceive the match exactly as a normal. The anomalous protanope, on the other hand, has shifted R/G sensitivies and thus a different match center.

11: Could be (B) or (D). As described above, the red, green, and yellow are all on confusion lines for the R/G dichromats. (A) and (C) have slightly wider ranges of hue matches (vs. normal), but shouldn't accept **all** mixtures.

12: (B) Remember that protans have "dimming of the red" (since their L wavelength pigment is shifted left/lower), so the yellow radiance/luminance setting indicates this.

Anomaloscope Answers 2

13: (D) Both (B) and (D) accept all hue matches, including the normals. But the normal luminance setting indicates the deutan. Their V(λ) curve is similar to the normal's. A protanope, on the other hand, would change the luminance to counteract their "dimming of the red".

14: Probably (C), if the range of mixtures is small. (Deuteranomalous trichromats are "green weak", but with normal luminance curves.) Note, however, that a deuteranope would also accept this match, plus all other mixture settings.

15: Probably (C), if the range of mixtures is small. (Protanomalous trichromats are "red weak", and have abnormal luminance curves.) Note, however, that a protanope would also accept this match, plus all other mixture settings.

Outline

OPTICS (PHYSIOLOGICAL): Perceptual Function / Color Vision

G. Color Perception
1. Chromatic discrimination (hue and saturation) for normal and defective
2. Color mixture and appearance
3. Color contrast, constancy, and adaptation
4. Color specification and colorimetry (CIE)
5. Spectral sensitivity of normal and defective color vision
6. Mechanisms of color deficiencies
7. Inherited anomalies of color vision
    a. Classification
    b. Inheritance patterns
    c. Color vision tests (e.g., pseudoisochromatic tests, arrangement tests
8. Acquired anomalies of color vision
    a. Classification
    b. Etiology
    c. Color vision tests
9. Conditions for color vision testing
10. Societal implications of color vision anomalies
    a. School
    b. Vocational requirements
    c. Patient interest
11. Patient management strategies
    a. Counseling
    b. Special aids

NBEO website answers

1: (B). For this, knowing the CIE diagram and confusion lines helps. Specifically, which lines pass through blue-green and white? Blue-green is in the middle of the left side of the CIE diagram, while white is in the middle.

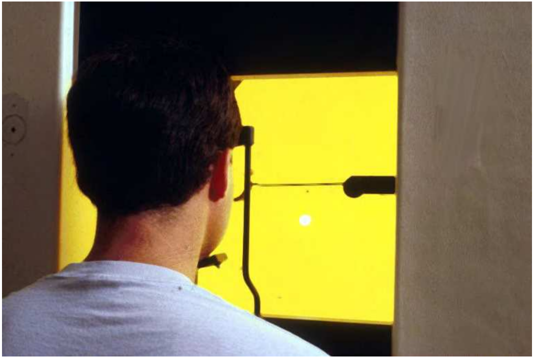
It's obviously not tritanopes, since their confusion lines radiate from the lower-left hand corner of the CIE diagram. The ones through white go from pure blue, to white, then to yellow. Trichromats don't have confusion lines (!), leaving choice (B). It would be difficult to distinguish between deuteranopes and protanopes here.

2: (A). First, the majority of inherited R/G color defects are X-linked recessive. For this question, we know that: the father is unaffected, while the wife may be a carrier. That means that it is possible that the daughter is a carrier or a son is color defective. BUT, the daughter could not be color defective. The father must be color defective in order for the daughter to be color defective.

Outline

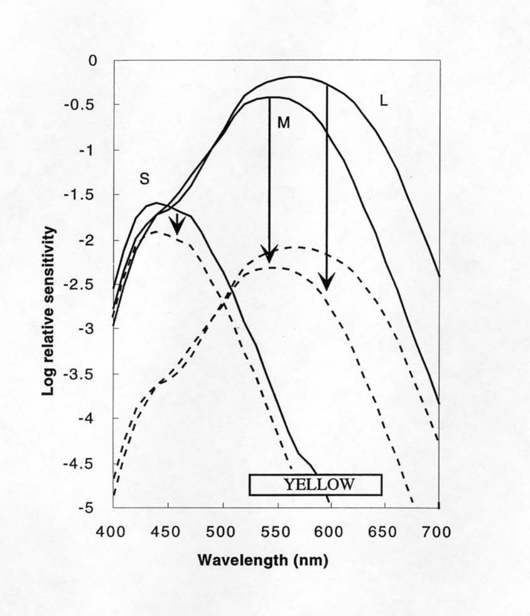
SWAP test

- Short Wavelength Automated Perimetry
- Humphrey Field Analyzer II (Model 700 and higher)
- Detect early glaucoma by isolating S cone function
- Useful for detecting other conditions



SWAP test theory

- SWAP works by adapting/bleaching M and L cones
- Broadband highpass filter passes above 530 (blocks λs below)



Miscellany

- Bezold-Brucke phenomenon: The hue of most wavelengths change slightly with different levels of luminance. See Schwartz Fig. 5-13.
- Abney effect: Constant hues are not on straight line from spectral locus to reference white. Makes “spider-web” pattern on CIE diagram.
- Grassman’s Laws for metamers: Metamers remain metamers under additivity, scaling, and associativity
- Color constancy: Colors appear perceptually same w/small changes in lighting and wavelength

CIE color matching functions

- Used to calculate chrom. coords from wavelength(s)
- $\overline{y}=V(\lambda)$
- Doesn't correspond to physical primaries
- Remember: any set of 3 primaries can be used to specify color system

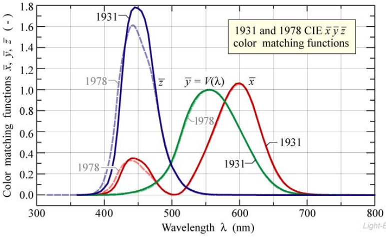


Fig. 17.1. CIE (1931) and CIE (1978) $\bar{x}\bar{y}\bar{z}$ color matching functions (CMFs). The $\bar{y}$ CMF is identical to the eye sensitivity function $V(\lambda)$. Note that the CIE 1931 CMF is the currently valid official standard.

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Wright color matching functions

- Wright's color matching functions (of given primaries)

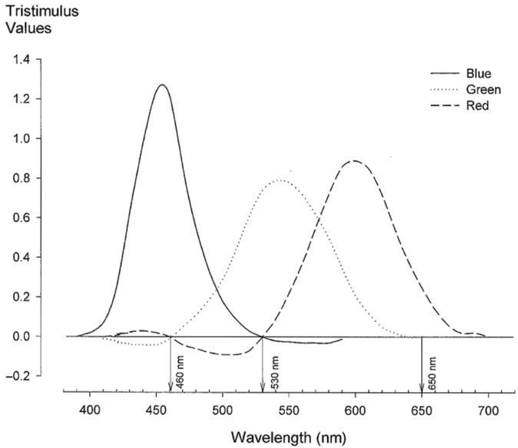
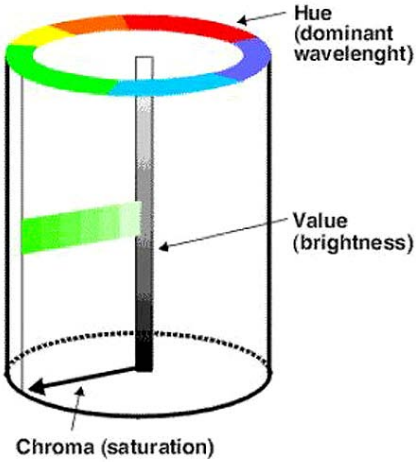


FIGURE 8.6 *Wright's color-matching functions. The tristimulus values on the y-axis are the relative amounts of the three primaries required to match the monochromatic wavelength indicated on the x-axis. The arrows indicate the positions of the three primaries used: 460, 530, and 650 nm. Note that the tristimulus values are 0 for two of the three primaries at these positions. Negative tristimulus values indicate that the primary had to be added to the reference side to achieve a color match. (Modified from WD Wright. Researches on Normal and Defective Colour Vision. St. Louis: Mosby, 1946.)*

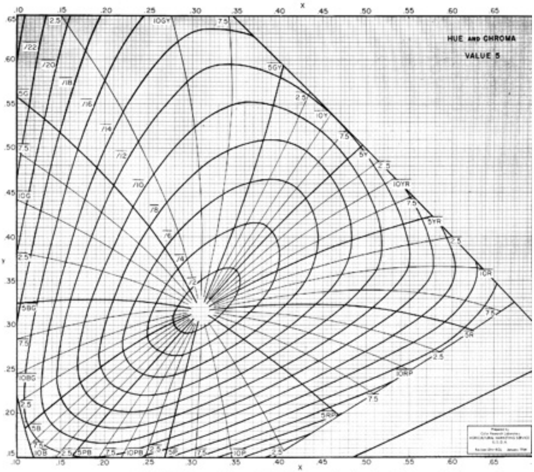
Munsell Cylinder

- Wright's color matching functions (of given primaries)
- Hue= color name. 100 hues divided into 10 segments of 10 hues e.g. 5 YR
- Value = lightness. Scale 1-10 (0 is black, 10 is white)
- Chroma = saturation. Scale 0-14 (0 is achromatic, 14 is saturated)
- Designated: H V/C e.g. 2 YR 5/10



Abney Hue Shift

- Abney effect: Constant hues are not on straight line from spectral locus to reference white.



CIE 1931 (x, y)-chromaticity diagram showing loci of constant hue and constant chroma at value 5/ of the Munsell renotation system (Dorothy Nickerson, private communication).

Notice that the lines of constant hue (radial like spokes on a wheel) are curved. This is because of the Abney effect.

MacAdam ellipses

- Metameric zones

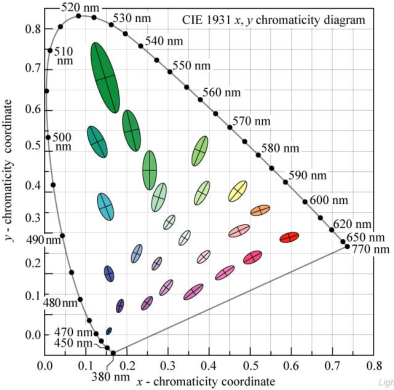


Fig. 17.5. MacAdam ellipses plotted in the CIE 1931 (*x*, *y*) chromaticity diagram. The axes of the ellipses are ten times their actual lengths (after MacAdam, 1943; Wright, 1943; MacAdam, 1993).

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CIE features

- A color monitor can display colors inside triangle