Color in Practice

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Presented in CS 294-164, Computational Color
Invited by Ren Ng

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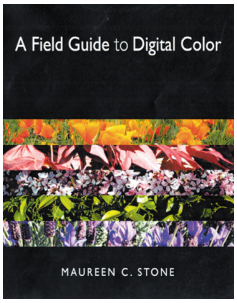

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Overview

Color models & colorimetry
Color for data visualization

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Modeling color

Physical World	Visual System	Mental Models
Lights, surfaces, objects, colorants	Eye, optic nerve, visual cortex	Red, green, brown Bright, light, dark, vivid, colorful, dull Identifies objects Directs attention Depends on context Experience Expectations …

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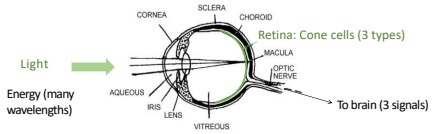
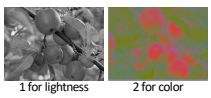
Color vision: Encoding light





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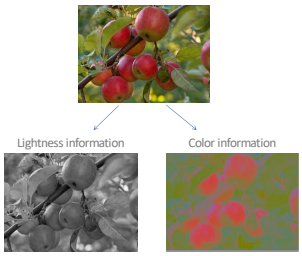
Fundamental difference: Shape from Color



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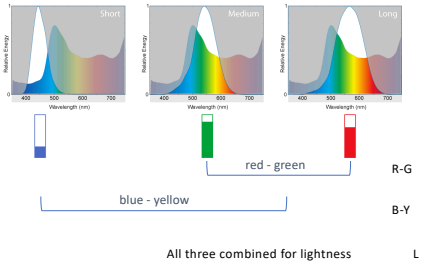
Encoded light: Lightness + differences



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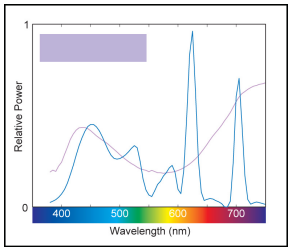
Encoded light: Two spectra can "look the same"

Metamerism



From M.Stone, *A Field Guide to Digital Color*, AK Peters 2003

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Color Vision Models

Physical World →	Visual System	
Light Energy	Cone Response	Opponent Encoding
Spectral distribution functions	Encode as three values	Separate lightness, chroma
F(λ)	L,M,S CIE XYZ	A,R-G,Y-B CIE xyY

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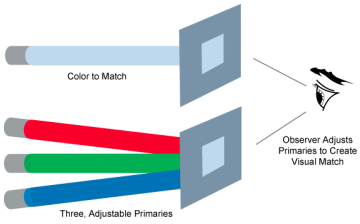
Color Matching Experiments

Match any color by adding any three (linearly independent) primaries



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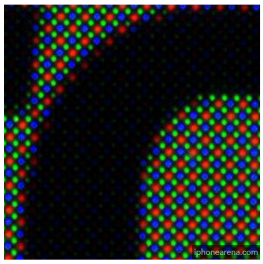
Tristimulus Values

Power of the primaries
- Define color by three numbers
- Specific to a set of primaries

Some restrictions apply
- Single colors
- Common viewing conditions
- 2-degree sample



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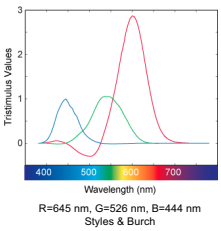
Color Matching Functions

To match any spectrum
- Multiply by CMF
- Integrate -> tristimulus values

To create a set of CMF's
- Pick three primaries
- Match monochromatic colors
- Plot values vs. wavelength



R=645 nm, G=526 nm, B=444 nm
Styles & Burch

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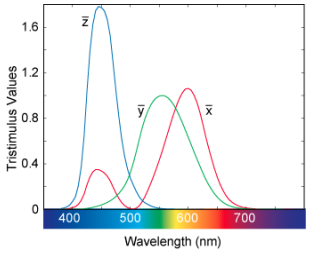
CIE Standards

Commission Internationale de l'Eclairage

Formalized color matching
- Standard primaries
- Standard observer

Standard representation
- Linear transform
- CMF's all positive
- Easy to compute



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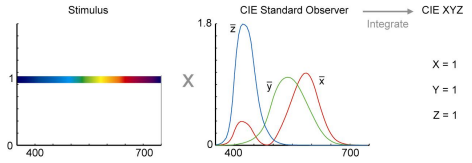
CIE Color Measurement

CIE Standard observer, tristimulus values (XYZ)

All spectra that measure the same XYZ value are indistinguishable



From *A Field Guide to Digital Color*, ©A.K. Peters, 2003

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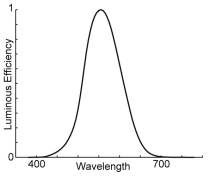
Intensity & Luminance

Intensity
- Integral of spectral distribution (power)

Luminance
- Intensity modulated by wavelength sensitivity
- Integral of spectrum × luminous efficiency function
- Luminance is CIE Y

Green and blue lights of equal intensity have different luminance values



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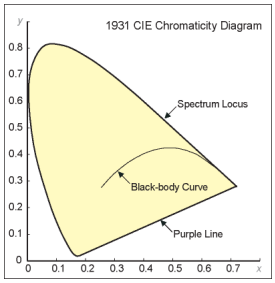
CIE Chromaticity (x,y)

Separate colorfulness from brightness

x = X/(X+Y+Z)
y = Y/(X+Y+Z)
z = Z/(X+Y+Z)

1 = x+y+z

XYZ = xyY



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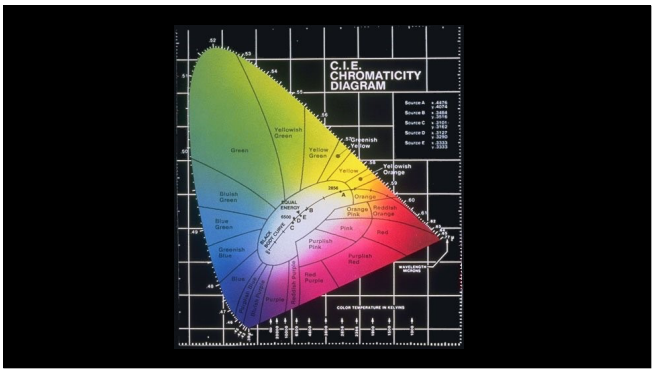

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Color as a Linear System

Grassman's additivity law
- If spectrum: s = a + b
- Then response: $XYZ_s = XYZ_a + XYZ_b$

Linear basis
- Color matching primaries
- 3x3 matrix conversions to other CMFs
- Linear transform between XYZ and RGB

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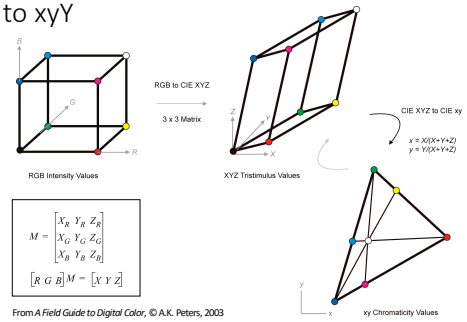
RGB to XYZ to xyY



Displayed intensities, not pixel values

"Gamma" curves

$$M = \begin{bmatrix} X_R & Y_R & Z_R \\ X_G & Y_G & Z_G \\ X_B & Y_B & Z_B \end{bmatrix}$$

$$[R\ G\ B]M = [X\ Y\ Z]$$

From *A Field Guide to Digital Color*, © A.K. Peters, 2003

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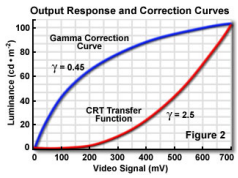
Luminance from RGB

$Y = rY_R + gY_G + bY_B$

Y_R, Y_G, Y_B
- Maximum luminance of RGB primaries
- Different for different displays

r,g,b
- Linear wrt luminance (intensity)
- Must compensate for "gamma"



Not a fixed equation!

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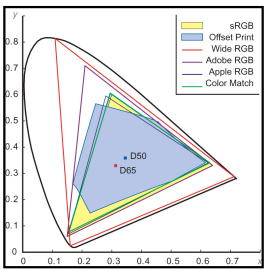
Common RGB Spaces

Gamma values
- Depends on display settings
- Typically around 2.2

sRGB

$$\gamma(u) = \begin{cases} 12.92u & u \le 0.0031308 \\ 1.055u^{1/2.4} - 0.055 & \text{otherwise} \end{cases}$$

- where u is R, G, or B.



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Summary

First level visual processing
- Trichromacy—Three cones respond to spectrum
- Metamerism—response, not spectrum

Colorimetry
- Color measurement
- Color matching functions & tristimulus values
- Color and RGB

But does what it LOOK like?

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Color Vision Models

Physical World	Visual System		Mental Models
Light Energy	Cone Response	Opponent Encoding	Perceptual Models
Spectral distribution functions	Encode as three values	Separate lightness, chroma	Hue, Lightness, Chroma
F(λ)	L,M,S CIE XYZ	A,R-G,Y-B CIE xyY	Munsell CIELAB

Appearance as a color, not as an object

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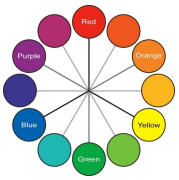
Hue (color wheel)
Consistent order, different spacings



Value
Perceived lightness

Chroma (saturation)
Intensity, purity, distance from gray

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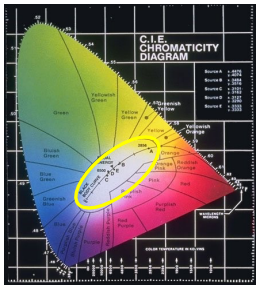
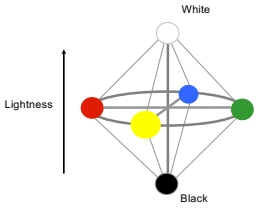
Tristimulus space: range of whites



Perceptual space: unique white



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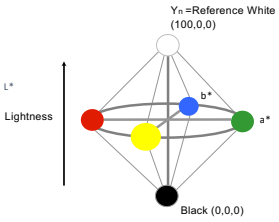
CIELAB

$$L^* = 116\, f\left(\frac{Y}{Y_n}\right) - 16$$
$$a^* = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right)$$
$$b^* = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right)$$

where

$$f(t) = \begin{cases} \sqrt[3]{t} & \text{if } t > \delta^3 \\ \frac{t}{3\delta^2} + \frac{4}{29} & \text{otherwise} \end{cases}$$
$$\delta = \frac{6}{29}$$



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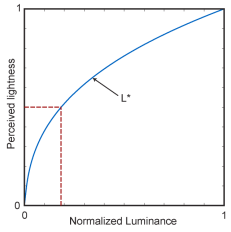
Luminance & L*

L* is a function of normalized luminance
Range 0 to100

$L^* = 116(Y/Y_n)^{1/3}-16$



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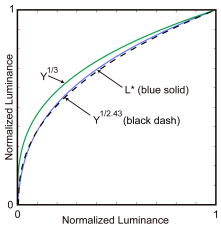
The L* Function

Combination power + linear functions
- Not 1/3 power
- Best fit is 1/2.43

$L^* \sim 100(Y/Yn)^{1/2.43}$



Similar issue in other non-linear lightness specifications

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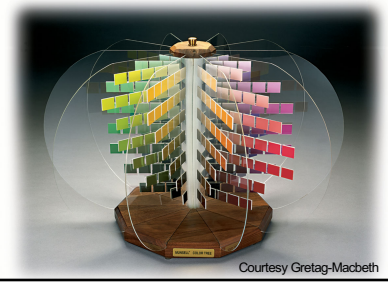
Munsell Atlas



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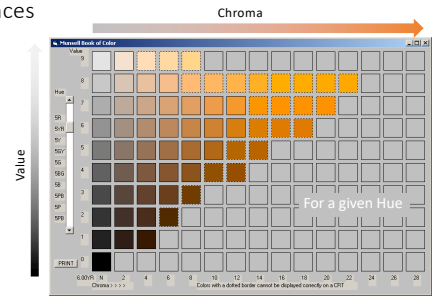
Uniform differences



Colors with a dotted border cannot be displayed correctly on a CRT

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Color Vision Models

Physical World		Visual System		Mental Models	
Light Energy		Cone Response	Opponent Encoding	Perceptual Models	Appearance Models
Spectral distribution functions		Encode as three values	Separate lightness, chroma	Hue, Lightness, Chroma	Adaptation Background Size …
F(λ)		L,M,S CIE XYZ	A,R-G,Y-B CIE xyY	Munsell CIELAB	CIECAM02 CIELAB*

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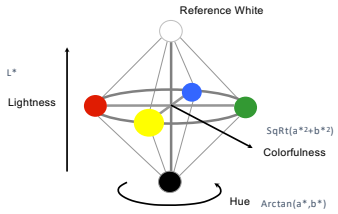
CIELAB

Hue, chroma, lightness
Not L* a* b*



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CIELAB as Appearance Model

Meets minimum requirements
- Based on CIE XYZ
- Predicts hue, chroma and lightness
- "Wrong von Kries" chromatic adaptation (XYZ vs. LMS)

For more detail, wait for Marc Fairchild

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Perception

Cone response
Lightness + color

Creation

RGB, HSV
CMY(K), BRY

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Measurement

Tristimulus values (XYZ)
CIELAB (L*,a*,b*)
CIELUV (L*,u*,v*)
…

Encoding

sRGB
Adobe RGB
rec 709 (video)
…

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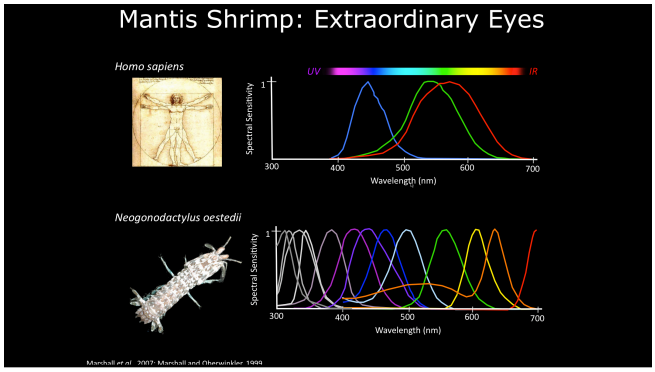
Mantis Shrimp: Extraordinary Eyes



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Color Vision Models

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F(λ)	L,M,S CIE XYZ	A,R-G,Y-B CIE xyY	Munsell CIELAB	CIECAM02 CIELAB*

Questions, discussion…

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Color for data visualization

Why use color?

Tableau data colors
- Intro
- Color for categories
- Color for quantity
- Designing for CVD

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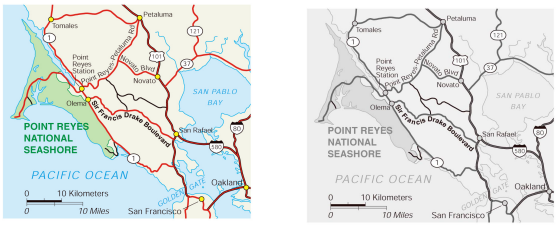
"Get it right in black and white"



Maps courtesy of the National Park Service (www.nps.gov)

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Tufte's fundamental uses

To label (identify or group)
To measure (color to quantity, color scales)
To represent or to imitate reality
To enliven or decorate

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"… avoiding catastrophe becomes the first principle in bringing color to information:
Above all, do no harm."

—E. R. Tufte

If you can't use color wisely,
it is best to avoid it entirely
Above all, do no harm

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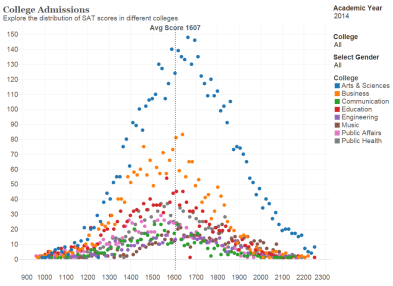
To Label: Categorical Palettes



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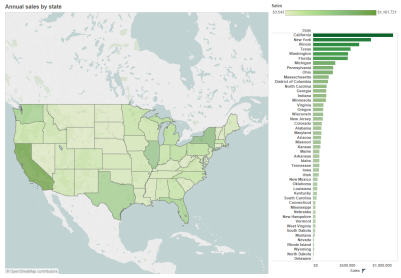
To Measure: Quantitative Palettes



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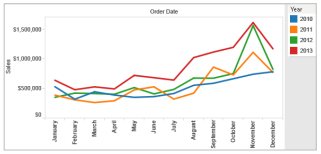
Different colorings tell different stories



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Similar, but still distinctly different

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Ordered colors for ordered relationships

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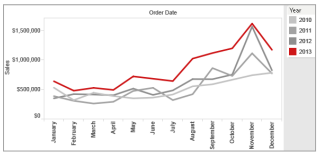
Contrasting color for emphasis



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Roles for color

To label (identify or group)
To measure (color to quantity, color scales)
To represent or to imitate reality
To enliven or decorate
To manage attention

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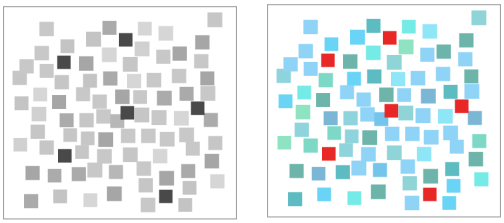
Contrast & Analogy



Contrast separates, analogy groups

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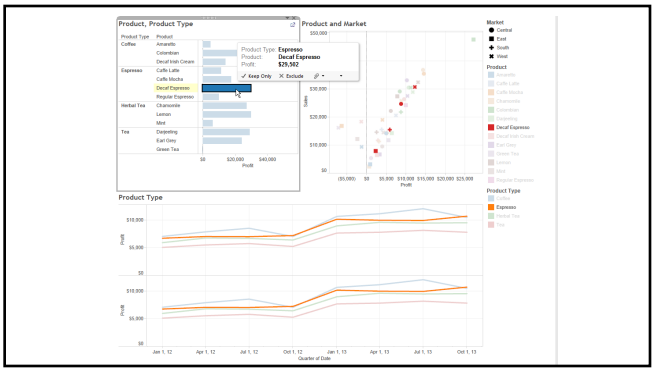

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Know what you want to show

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Color for data visualization

Why use color?
Tableau data colors
– Intro
– Color for categories
– Color for quantity
– Designing for CVD

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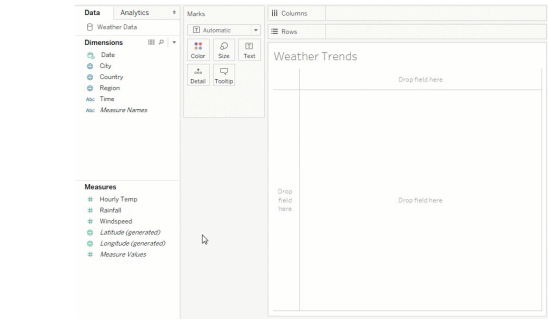

https://www.tableau.com/products/desktop

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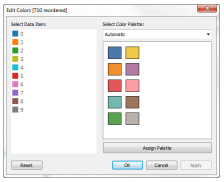
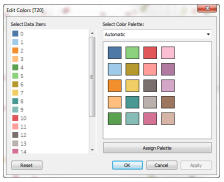
Default palettes (discrete categories)



Up to 10 data items



More than 10 items

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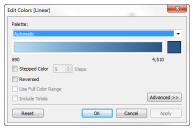
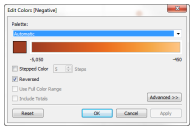
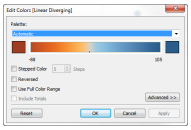
Default Palettes (continuous values)



All positive values



All negative values



Both (diverging)

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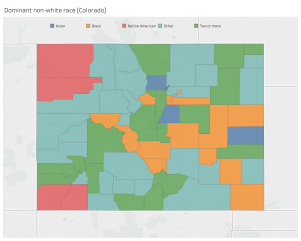
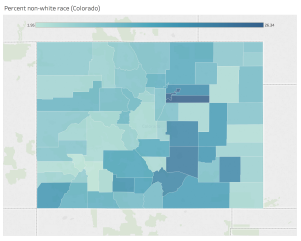
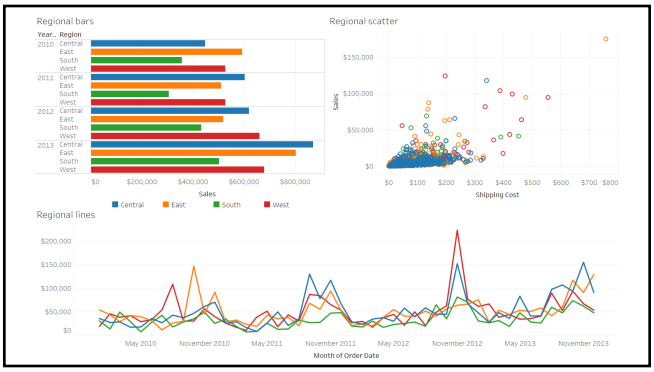


Categories: dominant non-white race

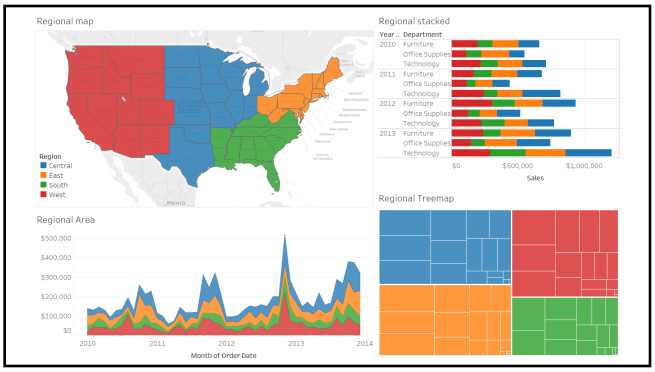


Quantity: percent non-white

58

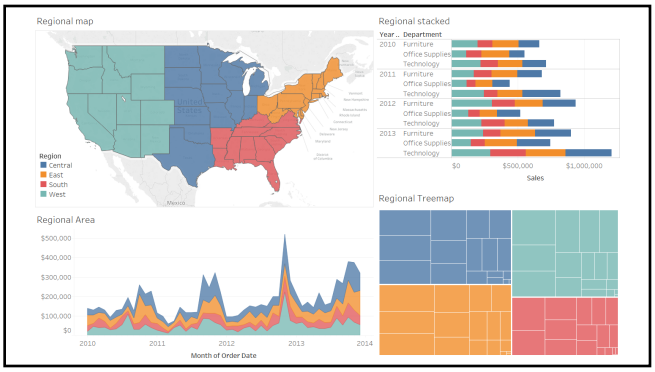


59



60

61



62

Principles for palettes

- Visibly distinct (including size, background, etc.)
- Easy to remember, to reference
- Make them beautiful

63

Principles for palettes

- Visibly distinct (including size, background, etc.)
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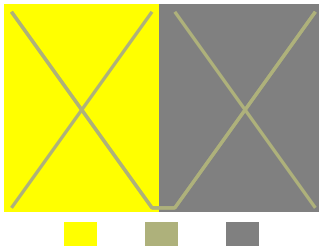
- Make them beautiful

64

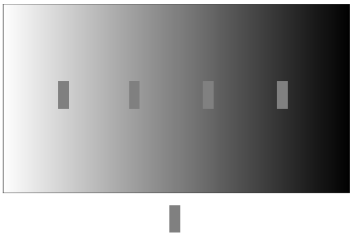
"Color is the most relative medium in art."

—Josef Albers, Interaction of Color



65

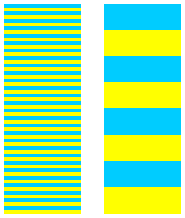
Gray is relative



From Stephen Few

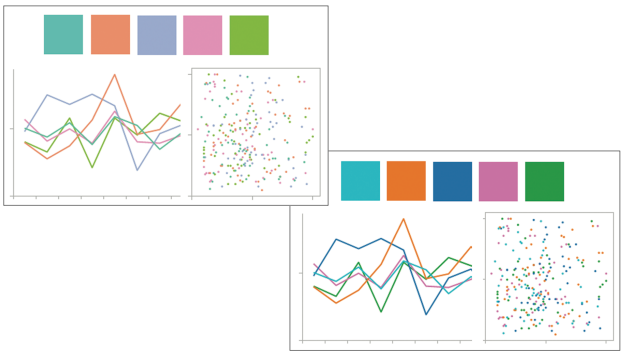
66

Color and contrast depends on size

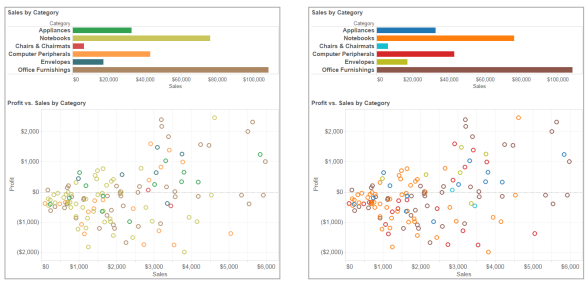


Redrawn from *Foundations of Vision*
© Brian Wandell, Stanford University

67



68

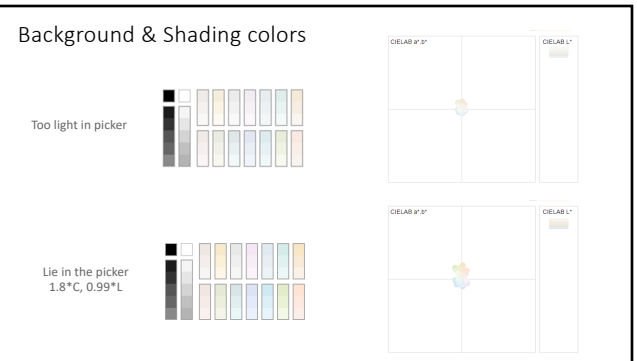


69

Background & Shading colors

Too light in picker

Lie in the picker
1.8*C, 0.99*L



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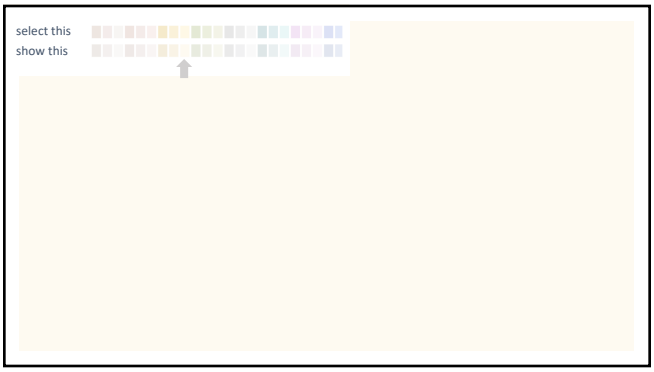

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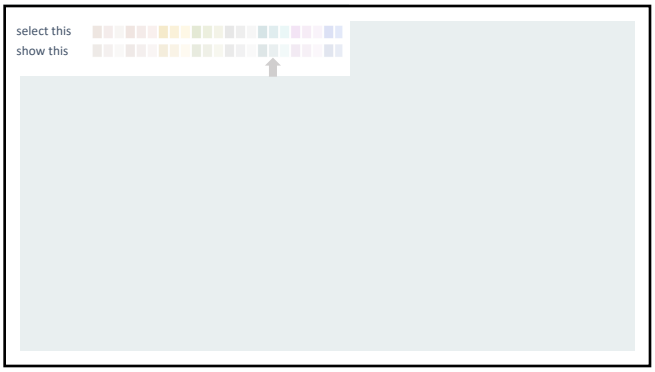
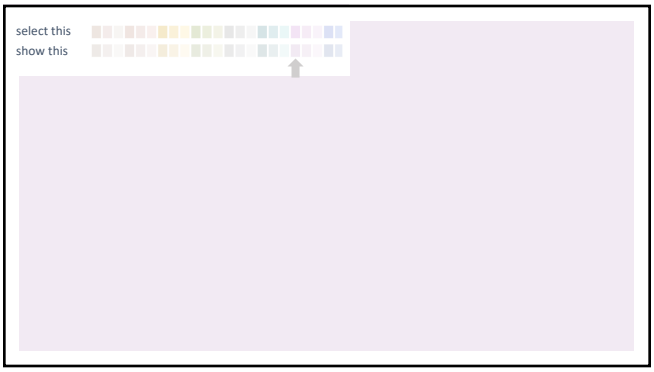


72



73

Principles for palettes

Visibly distinct (including size, background, etc.)

Easy to remember, to reference

Make them beautiful

74

red
yellow
blue
green
orange
brown
violet (purple)
black

From crayola.com

75

Color Names

Basic names (Berlin & Kay, 1969)
- Linguistic study of names across 20 languages
- Found 11 "basic names," similar linguistic evolution

World Color Survey (Kay, Berlin, Maffi, Merrifield, Cook, 2009)

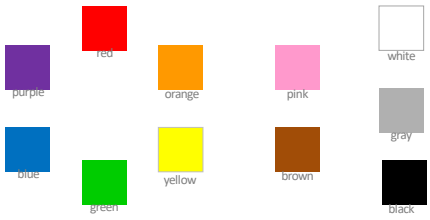
Through the Language Glass: Why the World Looks Different in Other Languages (Guy Deutscher, 2010)

How people think about color

76

Basic color names (English)

Red, orange, yellow, green, blue, purple, pink, brown, black, white, gray



77

Tableau 10 and 20 (2004)

Basic names + teal

Light-dark pairs

78

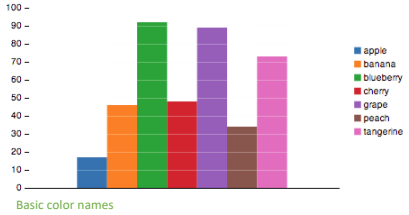
Tableau 10 and 20 (2016)

Basic names + teal

Light-dark pairs
Not all T10 in T20

79

Color and data semantics

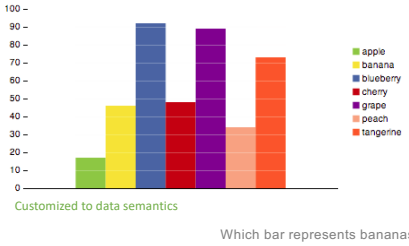


Basic color names

Which bar represents bananas?

80

Color and data semantics



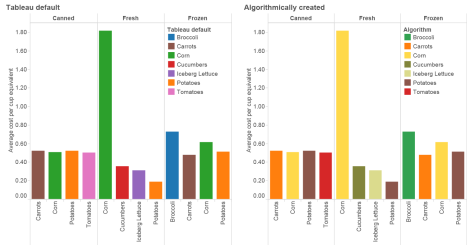
Customized to data semantics

Which bar represents bananas?

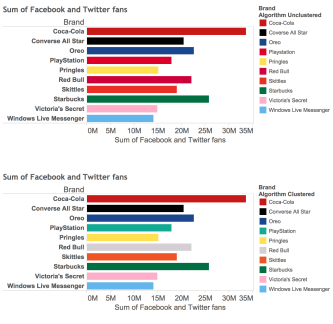
Lin, Fortuna, Kulkarni, Stone, Heer, Selecting Semantically-Resonant Colors for Data Visualization

81

Setlur & Stone



82



Find the best match

Avoid collisions

83

Colorability cases

The data is color
- CSS color names, hex codes

The data has defined colors
- Crayola colors, paint colors, Tableau colors
- Internal teams, process stages

The data suggests colors
- Colorable objects
- Brands, flags, sports teams

84

Principles for palettes

Visibly distinct (including size, background, etc.)

Easy to remember, to reference

Make them beautiful

Questions?

Cristy Miller
Visual Design

85

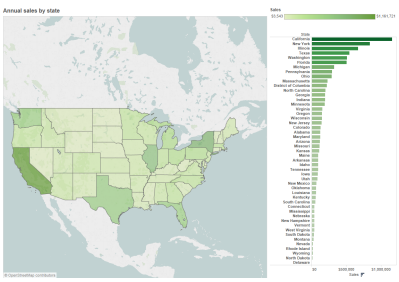
Color for data visualization

Why use color?

Tableau data colors
- Intro
- Color for categories
- Color for quantity
- Designing for CVD

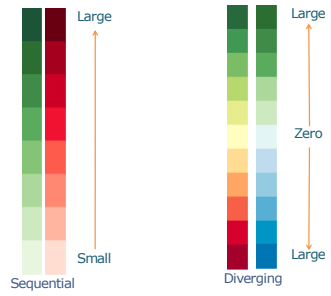
86

To Measure: Quantitative Palettes



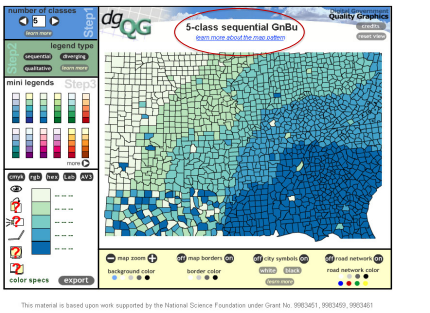
87

Types of color scales



From Cynthia Brewer

88

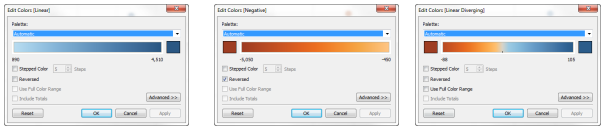


This material is based upon work supported by the National Science Foundation under Grant No. 9983451, 9983469, 9983461

www.colorbrewer.org

89

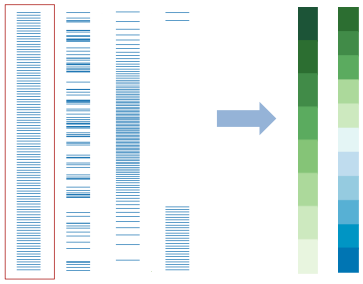
Default Palettes (continuous values)



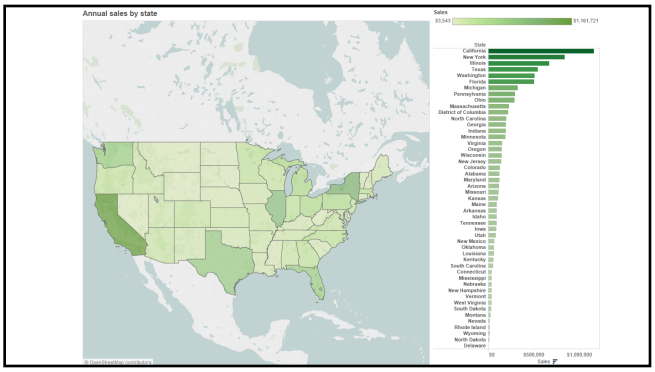
All positive values | All negative values | Both (diverging)

90

Real problem is data to color mapping

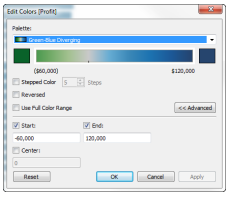


91

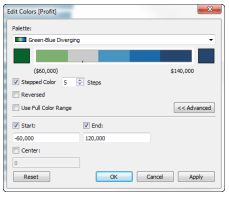


92

Simple controls



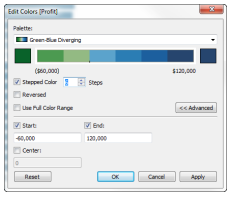
Color controls (top)
Data range controls (bottom)



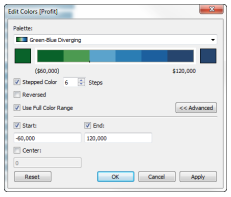
Step the colors (5-steps)

93

Simple controls

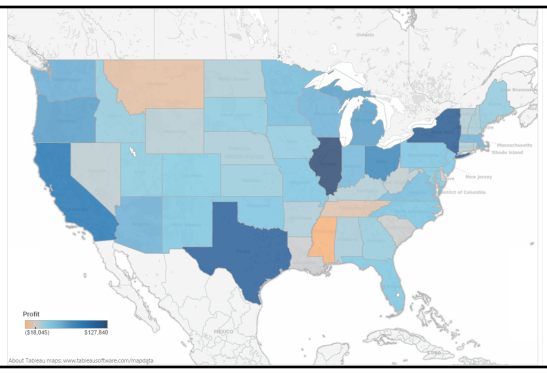


Step the colors (6-steps)



“use full color range”

94



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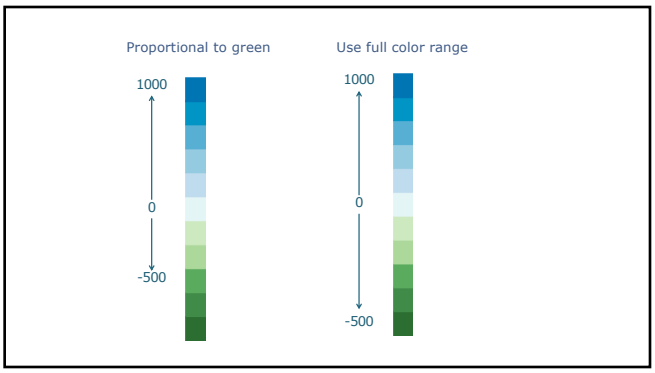

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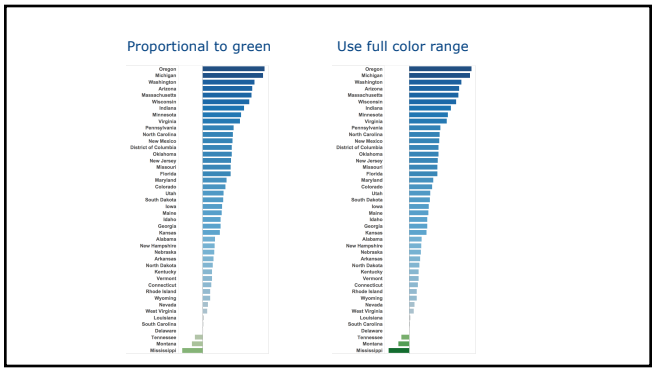

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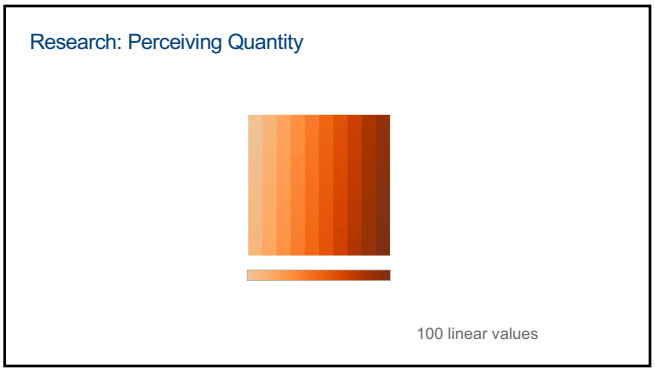

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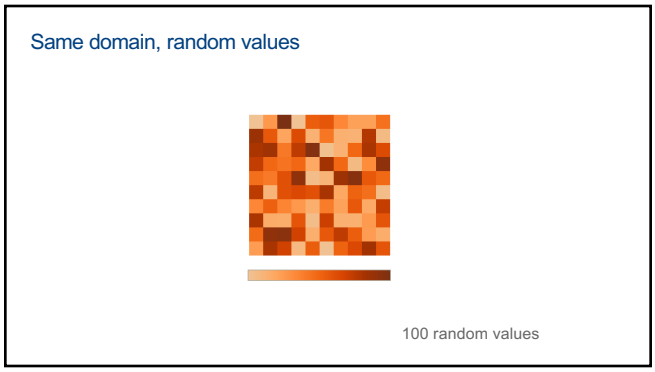

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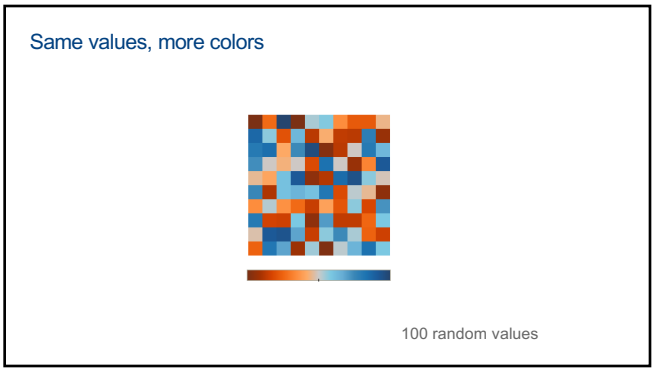

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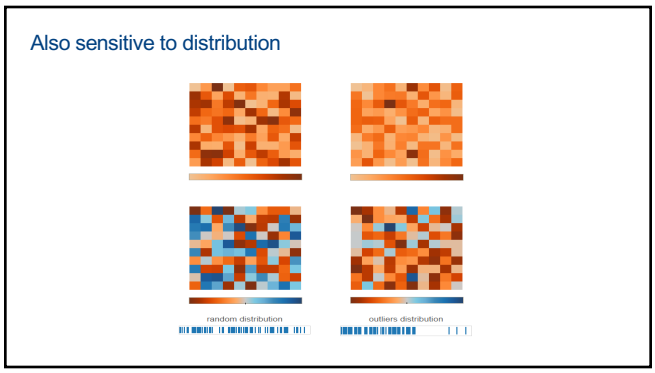

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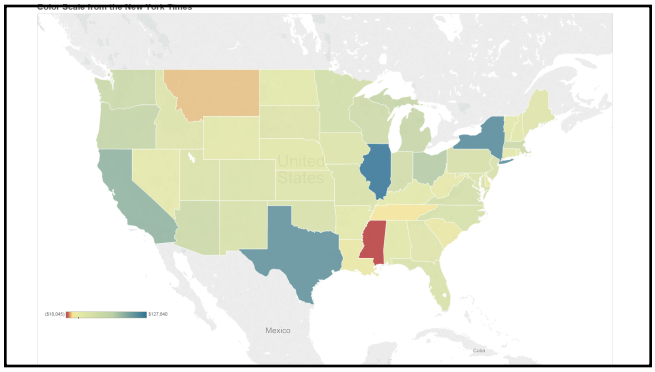
102



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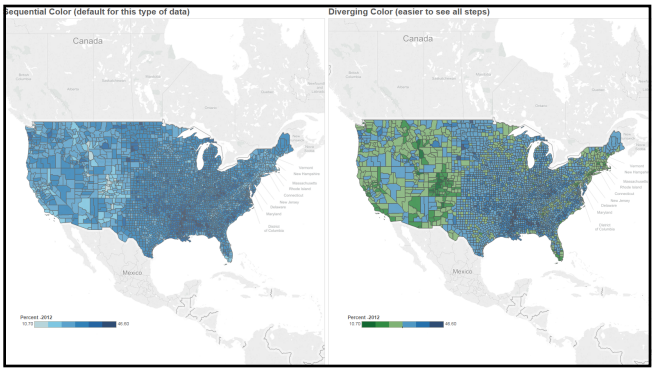

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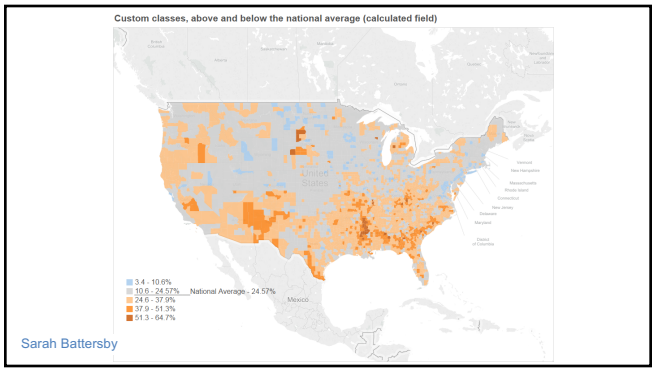

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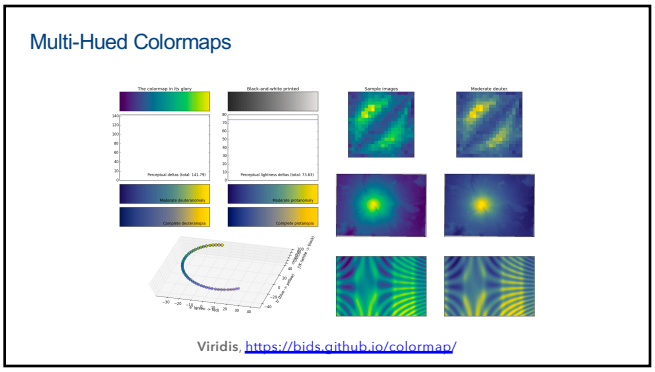

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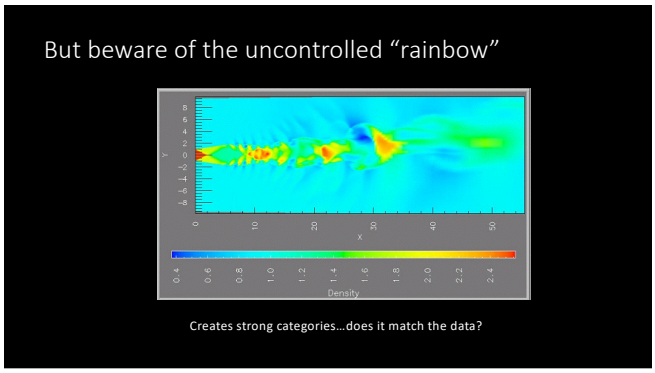

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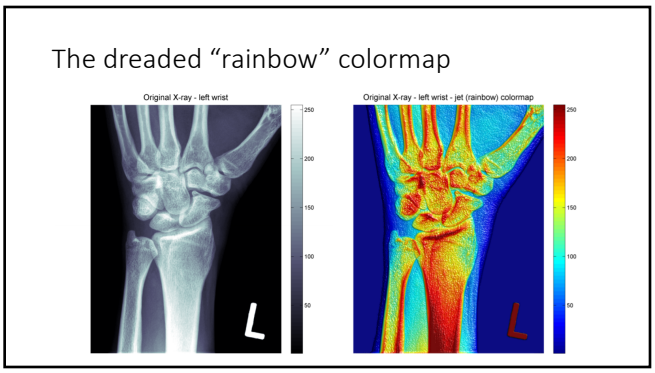

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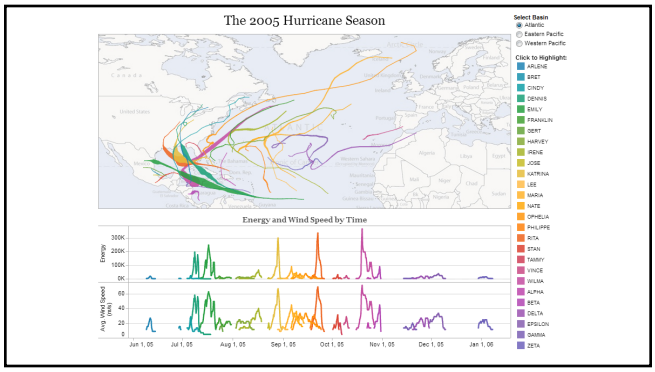

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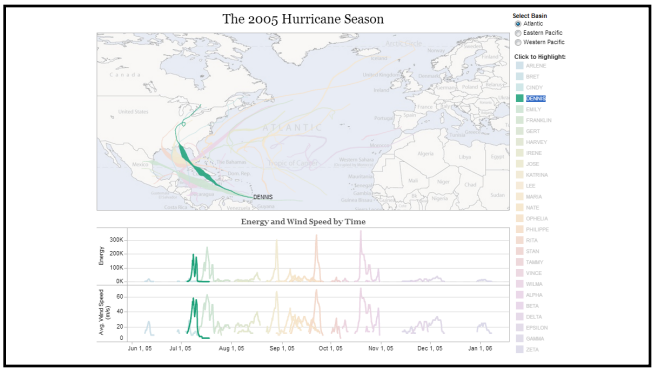

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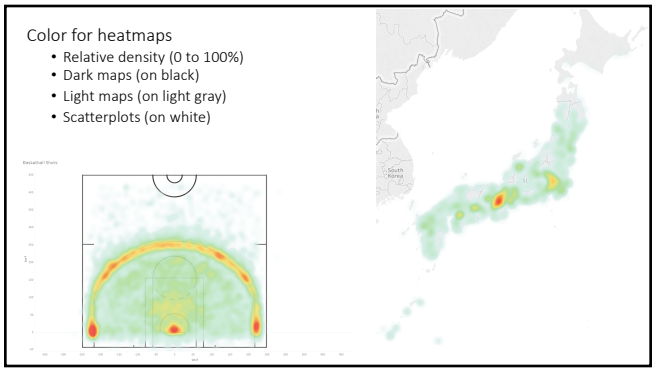

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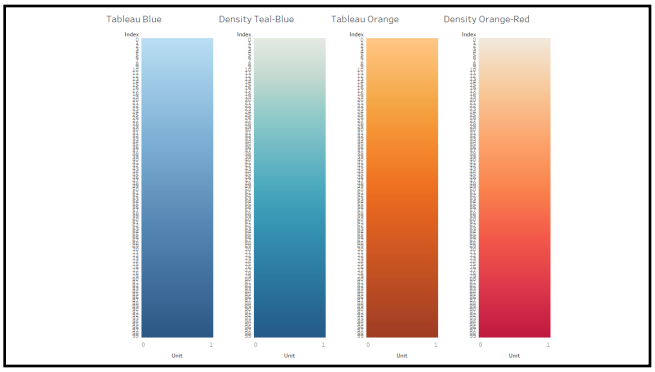

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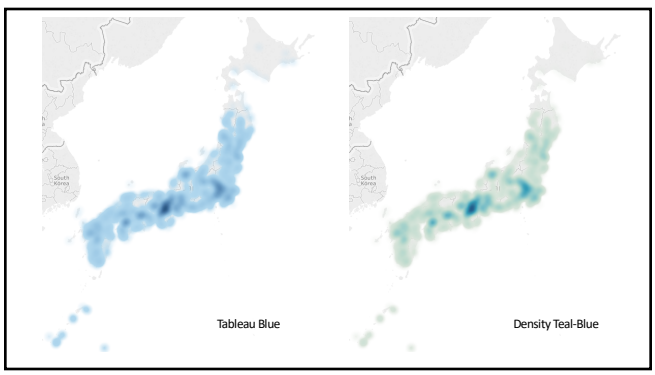

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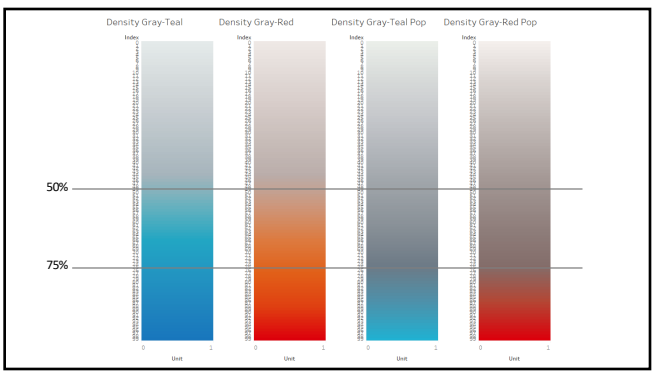

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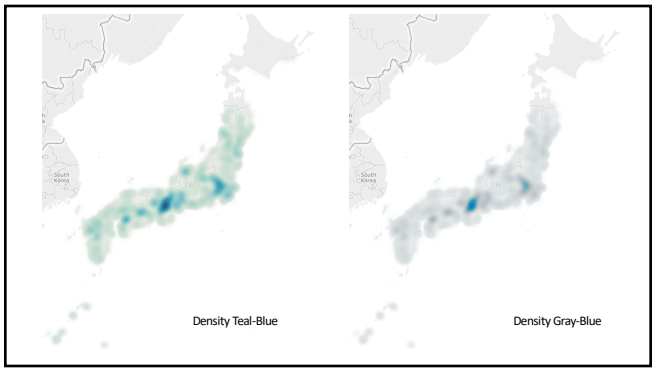

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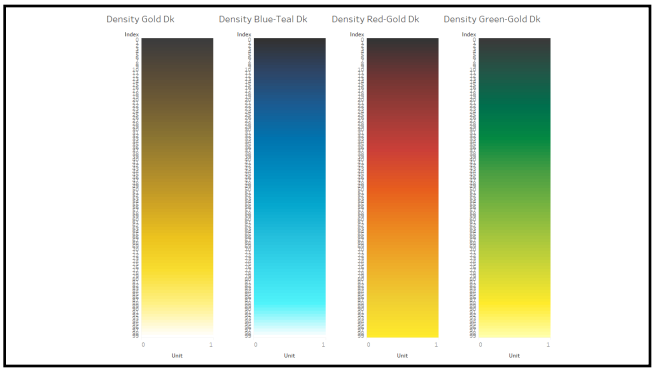

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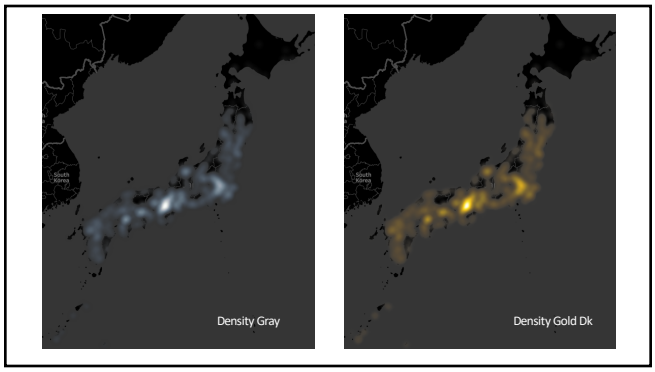

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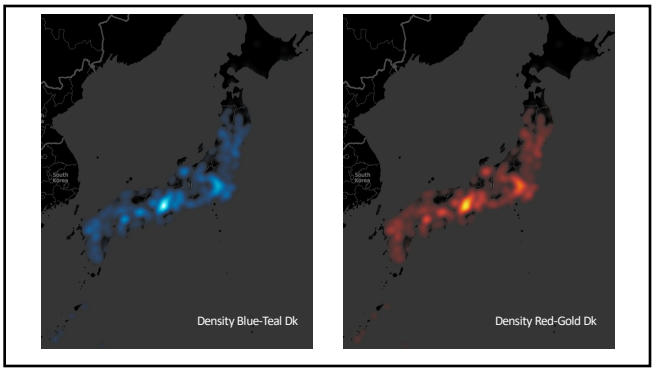

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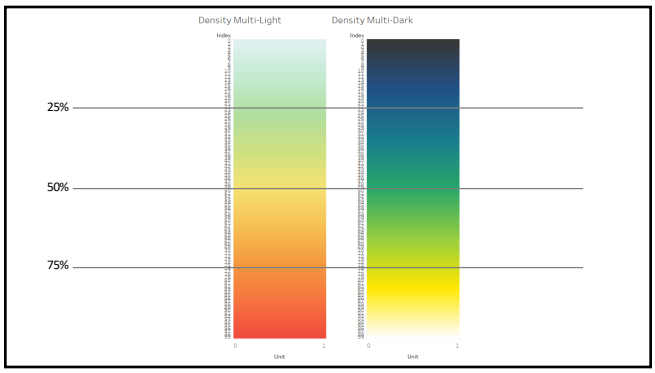

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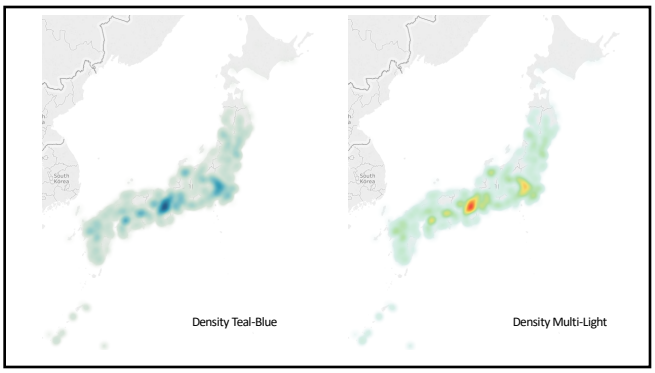

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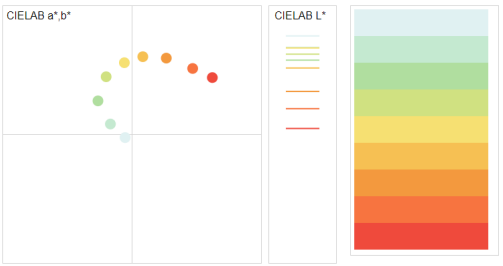
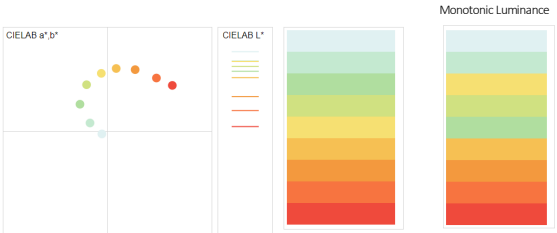


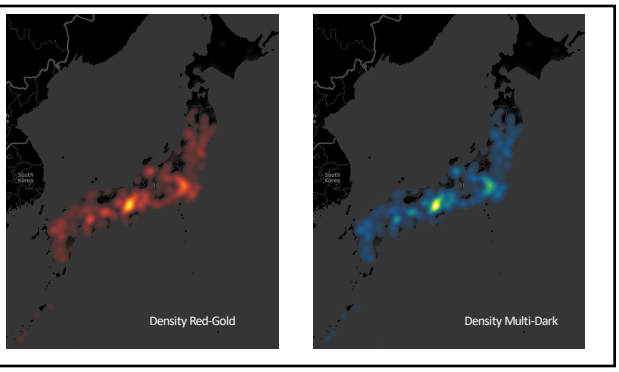
Not full hue circle, not maximally bright

121



Monotonic color contrast?

122



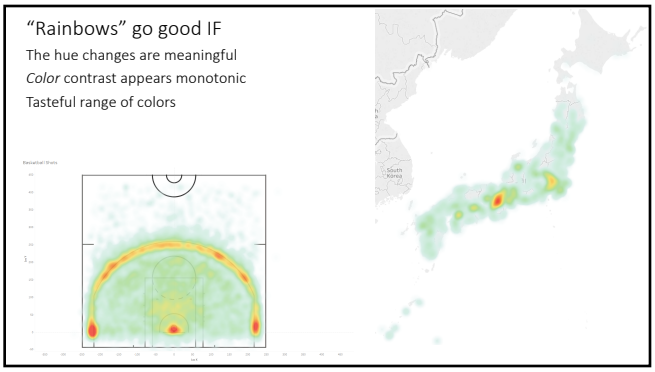
123

"Rainbows" go good IF

The hue changes are meaningful

Color contrast appears monotonic

Tasteful range of colors



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Color for data visualization

- Why use color?
- Tableau data colors
  - Intro
  - Color for categories
  - Color for quantity
  - Designing for CVD

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Designing for CVD

"normal"

"weak red-green"

Simulation from Coblinder

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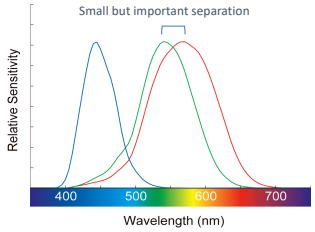
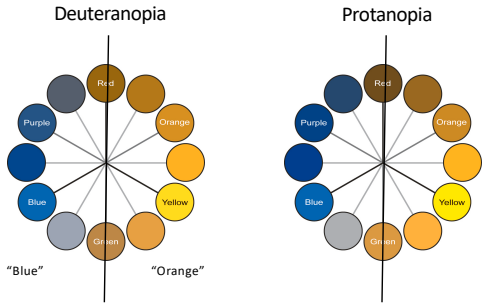
Most CVD involves problems with red-green



127



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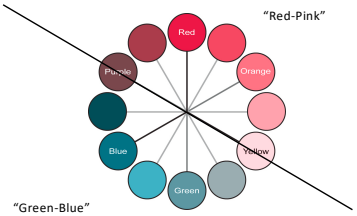
Tritanopia



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The real problem
Color name collisions

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Rules for accessibility

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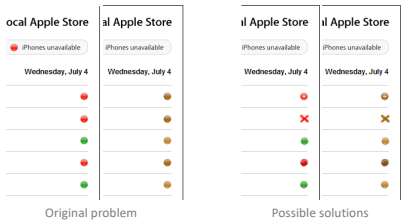
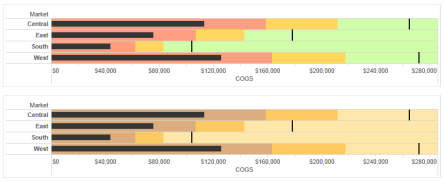
Avoid encoding by color alone



132

Encode with lightness



Deuteranope simulation

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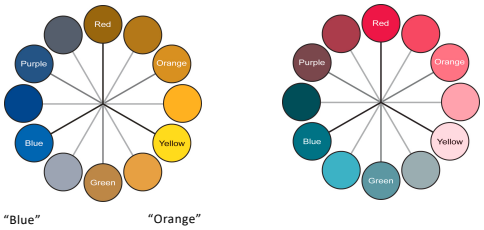
Use “safe” colors



“Blue” “Orange”

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Tableau 10 and CVD

Normal → Severe

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CVD Simulation

- Chromatic vision simulator: http://asada.tukusi.ne.jp/webCVS/index.html
- Color Oracle: http://colororacle.org/index.html

- Vischeck: http://www.vischeck.com/
- Built into current Adobe tools: View>Proof setup
- Coblis http://www.color-blindness.com/coblis-color-blindness-simulator/

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What we covered

Color models & colorimetry

Color for data visualization

- Why use color?
- Tableau data colors
  - Intro
  - Color for categories
  - Color for quantity
  - Designing for CVD

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Time check, questions?

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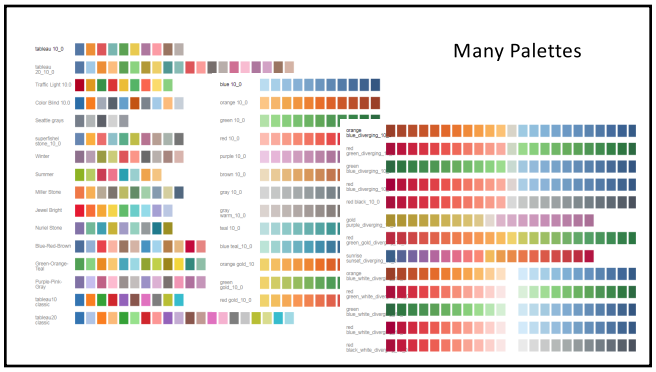
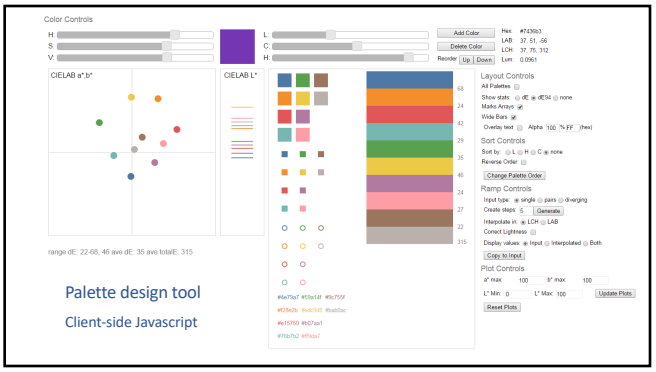


139



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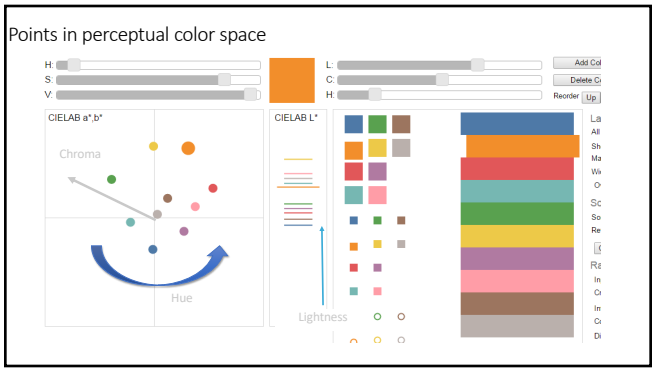

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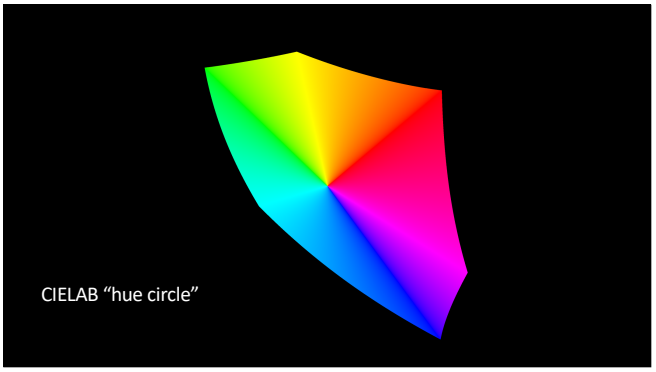

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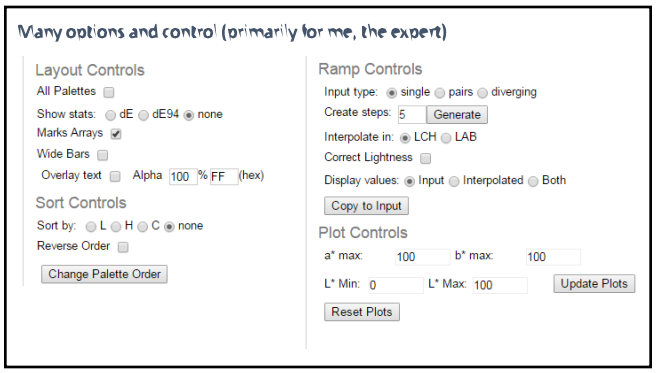

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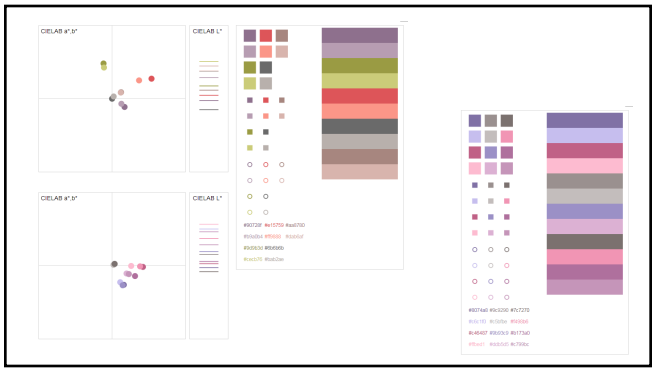

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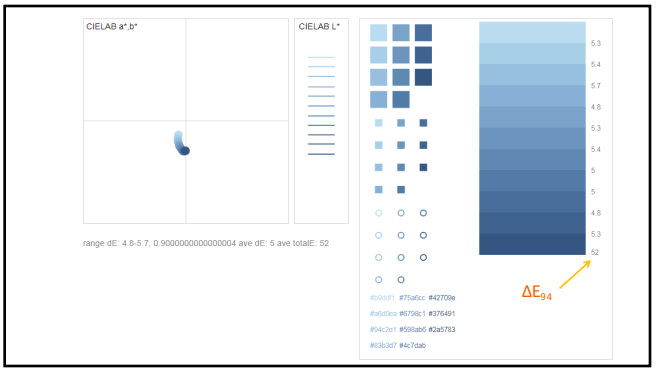
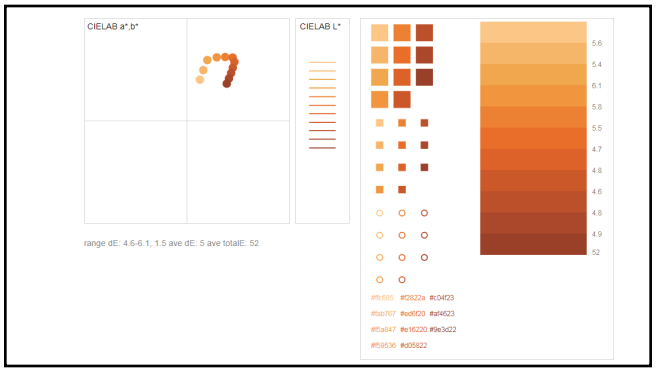
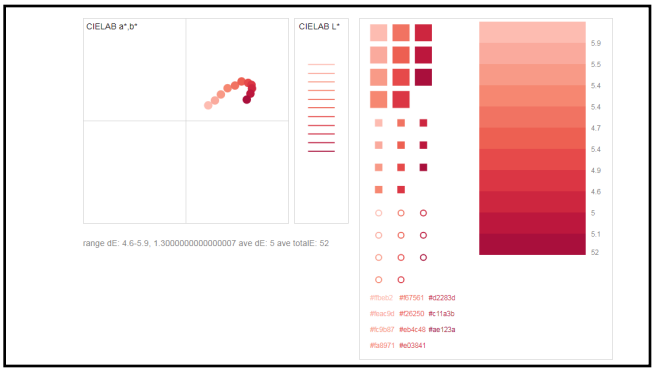


146



147



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