

Data Visualization

COLOR

Tea Tušar, Data Science and Scientific Computing, Information retrieval and data visualization

Overview

Motivation

Color perception

Color specification

Color use

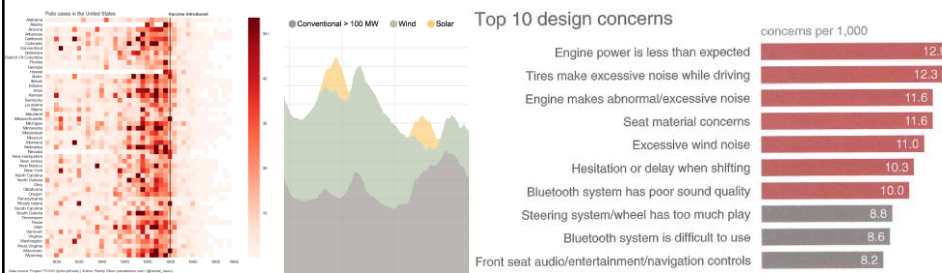
Motivation

Motivation

Color is a very powerful visual channel

Often used to

- Detect patterns (for example, in heat maps)
- Label data to distinguish among categories
- Highlight specific objects (to draw attention)



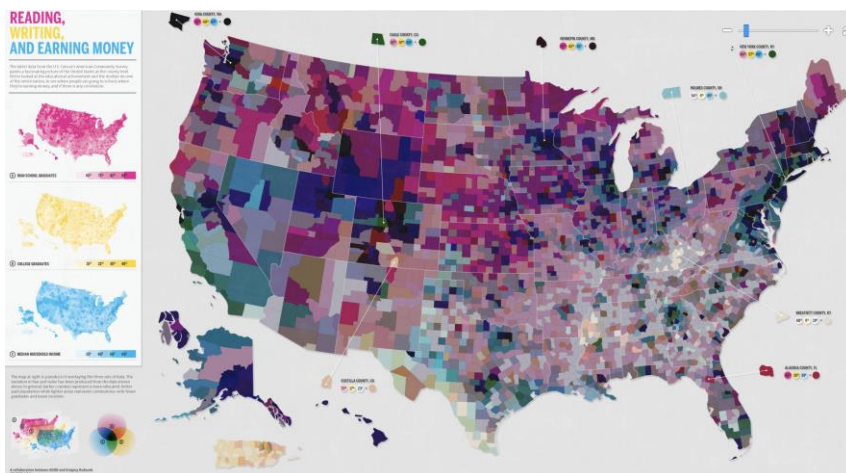
Color (mis)use

Above all, do no harm

Edward Tufte

5

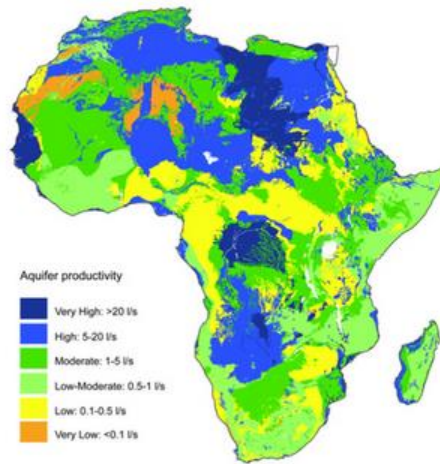
Color (mis)use



<https://www.good.is/infographics/america-s-richest-counties-and-best-educated-counties#open>

6

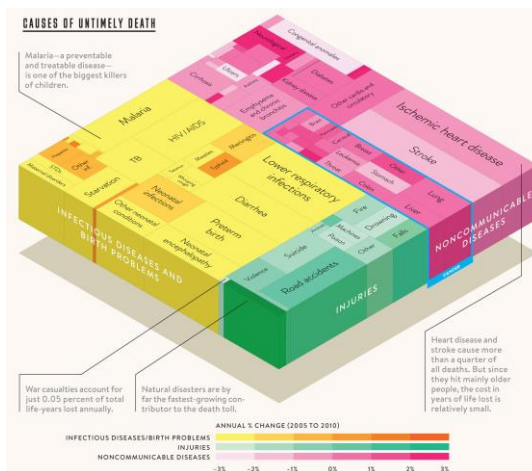
Color (mis)use



<https://www.newsecuritybeat.org/2012/05/full-extent-of-africas-groundwater-resources-visualized-for-the-first-time/>

7

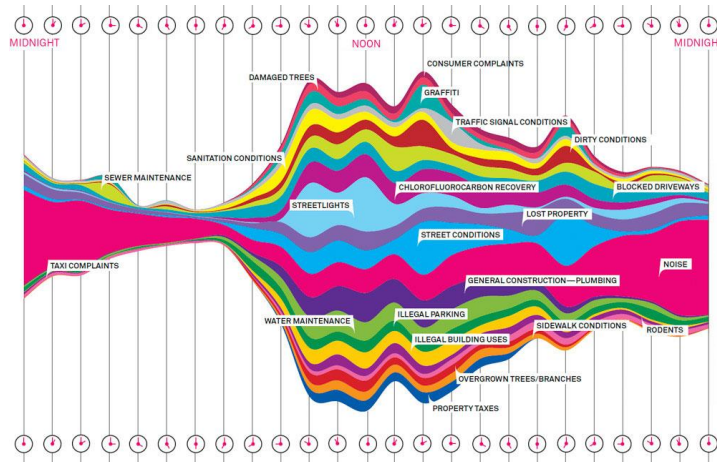
Color (mis)use



https://www.perceptualedge.com/images/example20problem_large.jpg

8

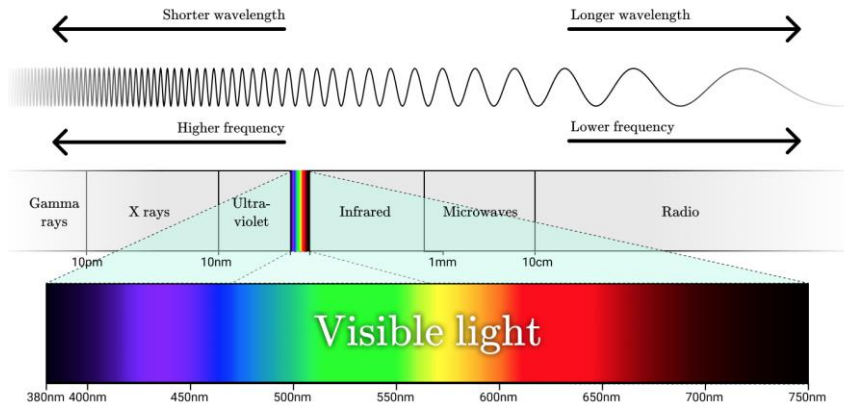
Color (mis)use



https://junkcharts.typepad.com/junk_charts/2010/11/making-charts-beautiful-without-adding-unnneeded-bits.html

Color perception

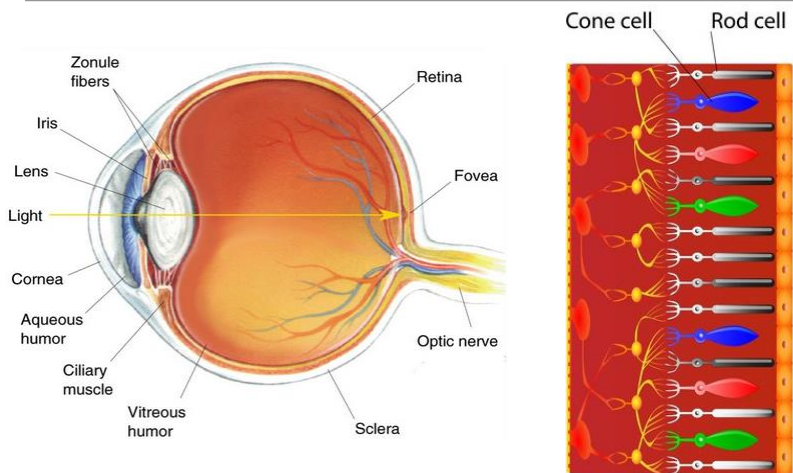
Light



<http://jamie-wong.com/post/color/>

11

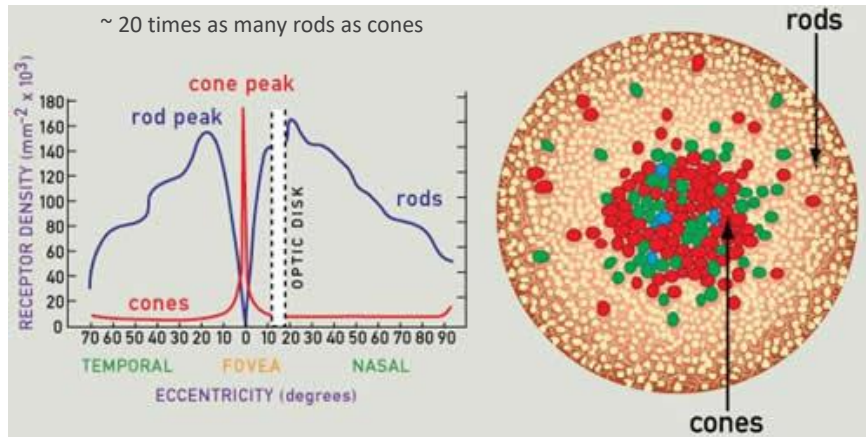
Human eye anatomy



<https://www.webrn-maculardegeneration.com/rods-and-cones.html>

12

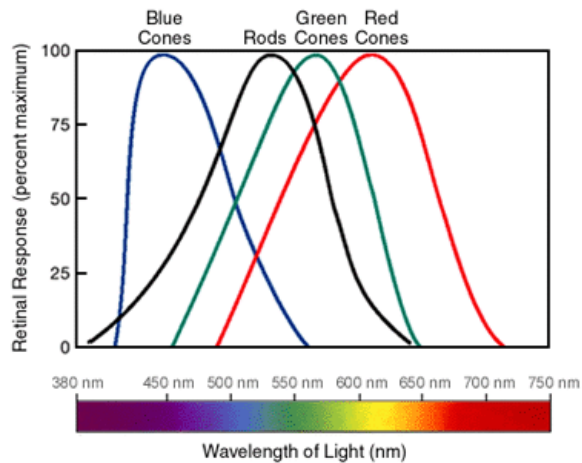
Rods and cones (photoreceptors)



<http://www.webexhibits.org/causesofcolor/1G.html>

13

Sensitivity of rods and cones



<https://askabiologist.asu.edu/rods-and-cones>

14

Trichromatic theory of color

We have three kinds of color receptors

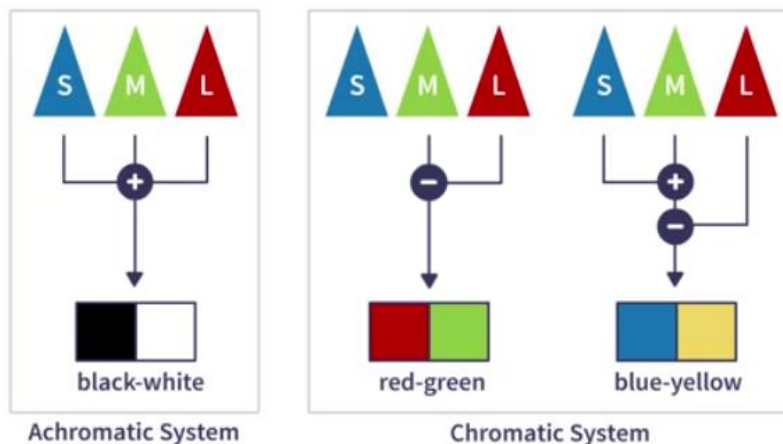
- S = short wavelength (“blue” cones)
- M = medium wavelength (“green” cones)
- L = long wavelength (“red” cones)

Any visible color can be expressed as a combination of three primary colors

However, we don't perceive color in terms of amount of blue, green and red

15

Color opponent process theory

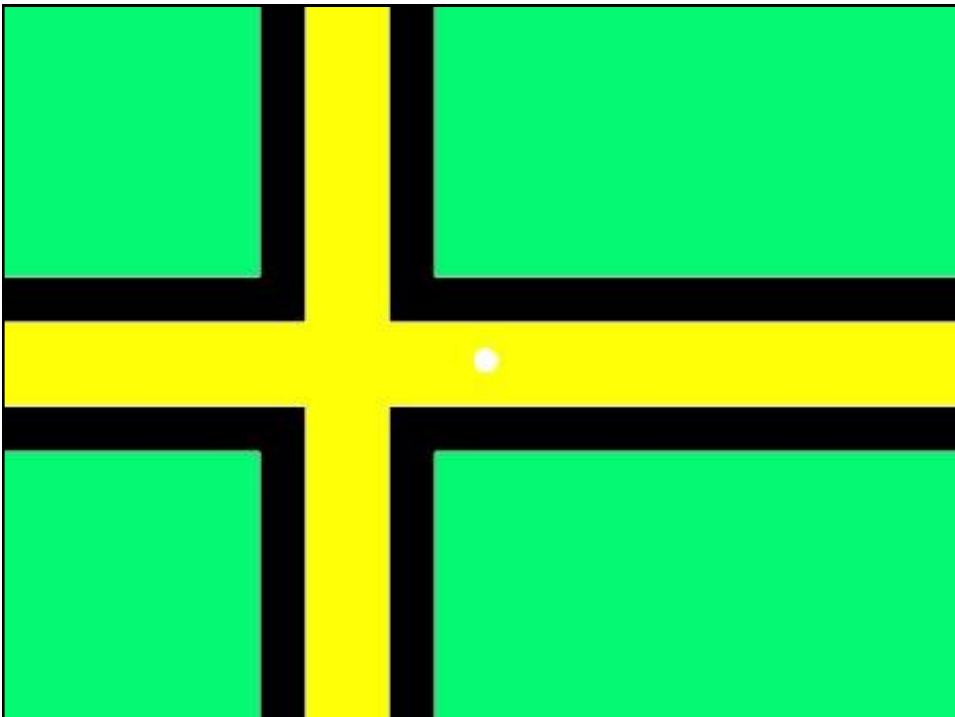


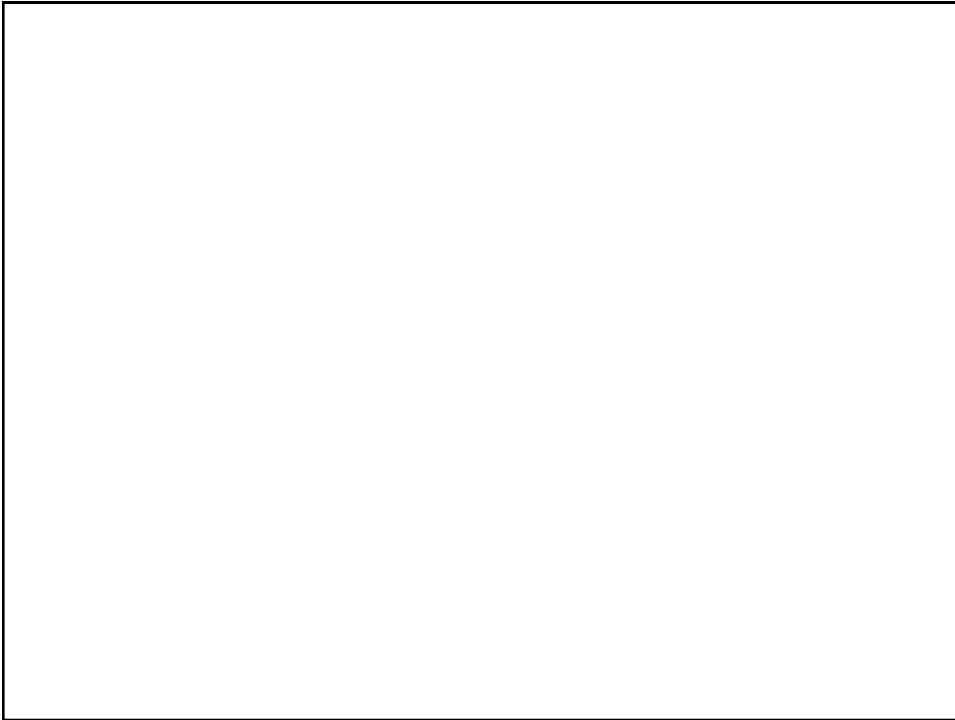
Color opponent process theory

Facts that seem to corroborate the theory

- We don't perceive neither the "red-green color" nor the "blue-yellow color"
- Colorblind people tend to be blind on exactly these two axes (most often red-green and least often blue-yellow)
- The following example

17





Color opponent process theory

Facts that seem to corroborate the theory

- We don't perceive neither the "red-green color" nor the "blue-yellow color"
- Colorblind people tend to be blind on exactly these two axes (most often red-green and least often blue-yellow)
- The previous example

After staring at these colors, the sensors inhibit them and you see their opposites

Color perception summary

Human eye

- Rods (low light conditions, no colors)
- Cones (colors when enough light)

Trichromacy

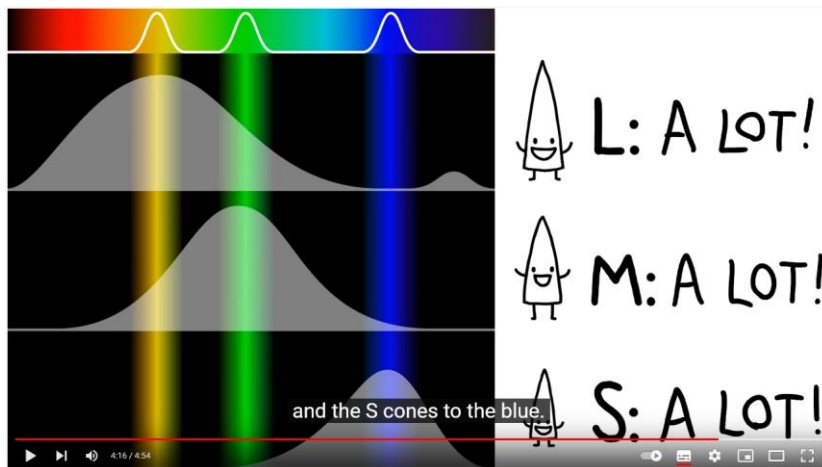
- Three receptors of color

Opponent process theory

- Signals from the eye transformed in the visual cortex to black-white, red-green and blue-yellow axes

21

Color perception



<https://www.youtube.com/watch?v=poL7nDmqjmk>

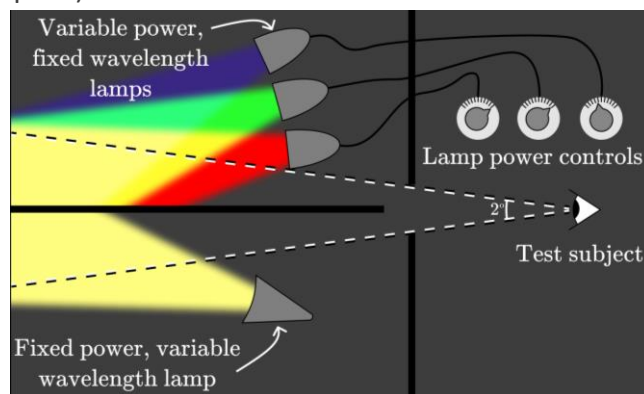
22

Color specification

23

Color specification

Every color can be expressed as the sum of three colors (in a 3-D space)



<http://jamie-wong.com/post/color/>

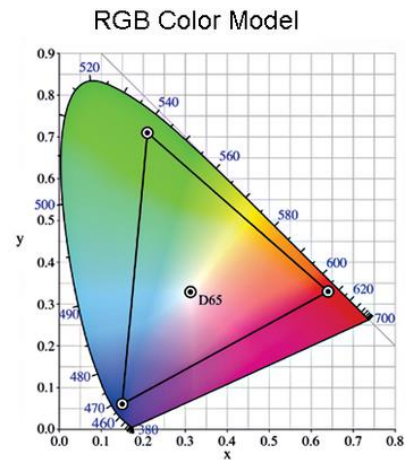
24

Color spaces

A color space is a (3-D) system that describes colors

The **gamut** of the color space is the whole set of colors that can be reproduced by this color space

Not all color spaces are equivalent



https://www.researchgate.net/figure/RGB-Color-Model-and-CIE-Lab-Color-space_fig3_41669565

25

Properties of color spaces

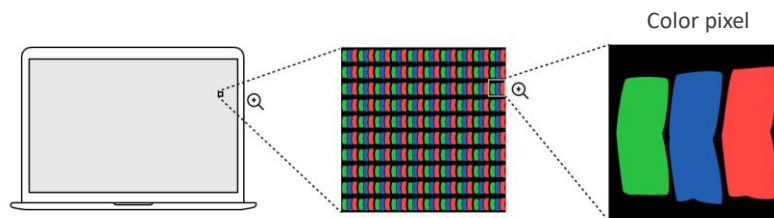
	Intuitive	Perceptually uniform
RGB		
HSL / HSV		
CIE Lab		
CIE LCh / HCL		

26

RGB

- R = red
- G = green
- B = blue

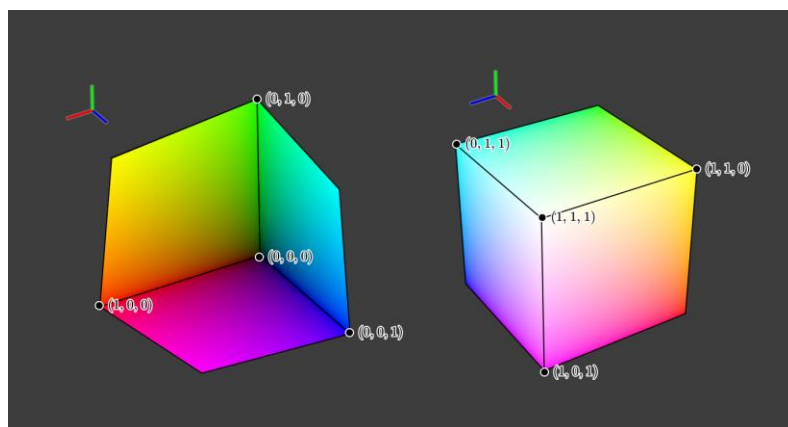
Commonly used in digital devices



<http://jamie-wong.com/post/color/>

27

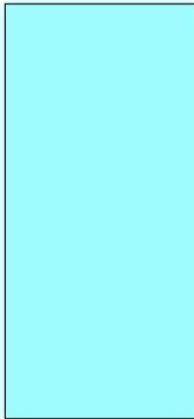
RGB



<http://jamie-wong.com/post/color/>

28

RGB



Red - Currently set to 126



Green - Currently set to 255



Blue - Currently set to 255



<http://www.csfieldguide.org.nz/en/interactives/rgb-mixer/index.html>

29

RGB

G and B fixed (G = 192, B = 0), changes only in R



R = 5

R = 55

R = 105

R = 155

R = 205

R = 255

30

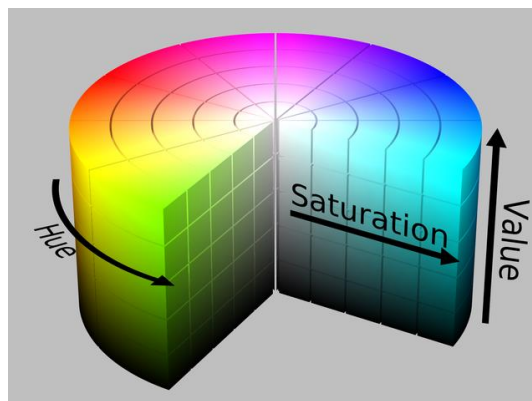
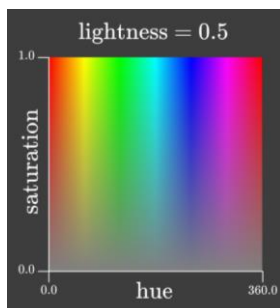
Properties of color spaces

	Intuitive	Perceptually uniform
RGB	✗	✗
HSL / HSV		
CIE Lab		
CIE LCh / HCL		

31

HSL / HSV

- H = hue
- S = saturation
- L/V = lightness/value



https://en.wikipedia.org/wiki/HSL_and_HSV
<http://jamie-wong.com/post/color/>

32

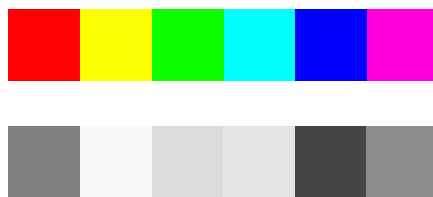
HSL / HSV



<http://hslpicker.com>

33

HSL / HSV



34

Properties of color spaces

	Intuitive	Perceptually uniform
RGB	✗	✗
HSL / HSV	✓	✗
CIE Lab		
CIE LCh / HCL		

35

CIE Lab

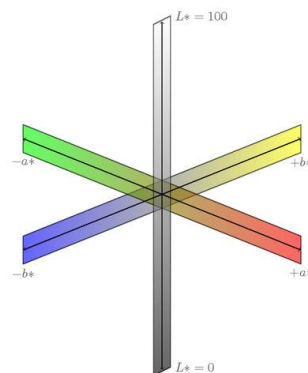
CIE (International Commission on Illumination)

Specified according to the opponent process theory

- L^* = lightness
- a^* = green-red axis
- b^* = blue-yellow axis

Designed to be perceptually linear

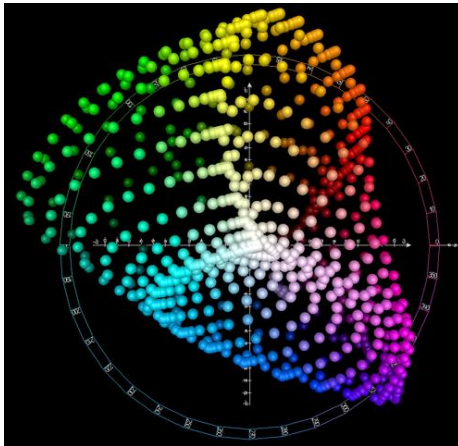
A nonlinear transformation of color wavelengths



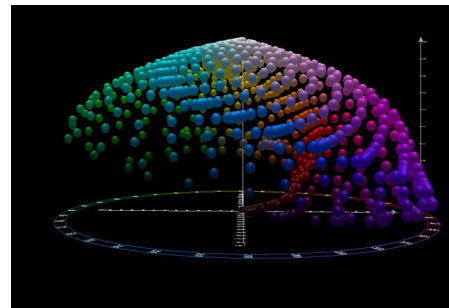
<http://www.texample.net/tikz/examples/cielab/>

36

CIE Lab



Top view



Front view

https://en.wikipedia.org/wiki/CIELAB_color_space

37

CIE Lab

David Johnstone

Lch and Lab colour and gradient picker

Page background colour:

Colour selection mode:

Number of stops:

L: 60

a: -100

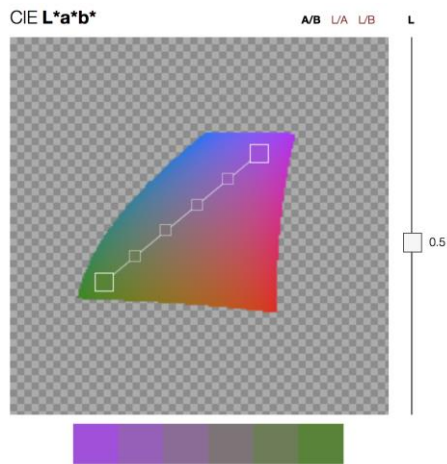
b: 3



<http://davidjohnstone.net/pages/lch-lab-colour-gradient-picker>

38

CIE Lab



<https://www.vis4.net/labs/colorvis/embed.html?m=lab&gradients=6>

39

Properties of color spaces

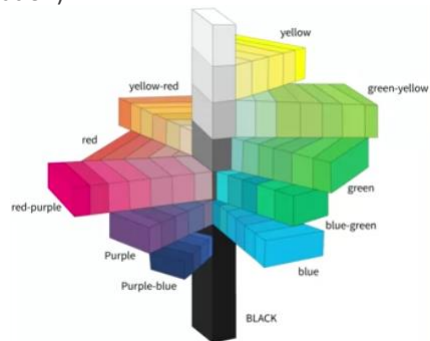
	Intuitive	Perceptually uniform
RGB	✗	✗
HSL / HSV	✓	✗
CIE Lab	✗	✓
CIE LCh / HCL		

40

CIE LCh / HCL

Transformation of CIE Lab to cylindrical coordinates

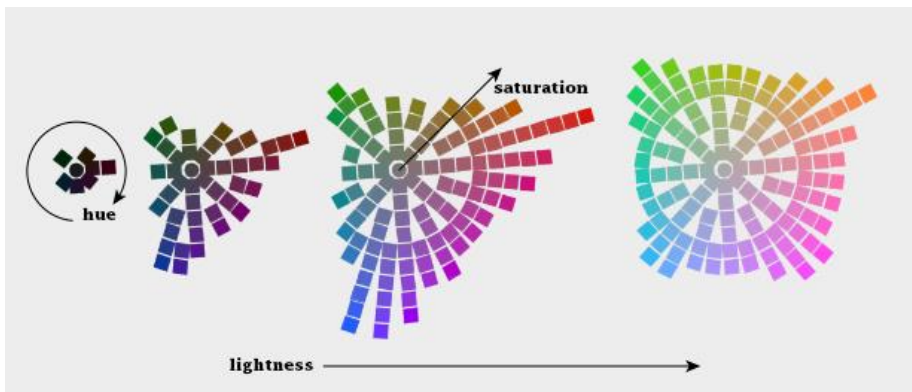
- L* = lightness (as in CIE Lab)
- C* = chroma (corresponds to saturation)
- h = hue



<https://www.coursera.org/learn/information-visualization-applied-perception>

41

CIE LCh / HCL



<https://earthobservatory.nasa.gov/blogs/elegantfigures/2013/08/>

42

CIE LCh / HCL

David Johnstone

Lch and Lab colour and gradient picker

Page background colour:

Colour selection mode:

Number of stops:

L: 79

c: 63

h: 58



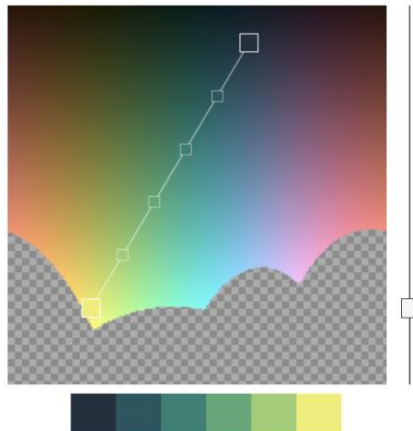
<http://davidjohnstone.net/pages/lch-lab-colour-gradient-picker>

43

CIE LCh / HCL

Hue Chroma Lightness

HL CL H/C c



<https://www.vis4.net/labs/colorvis/embed.html?m=hcl&gradients=6>

44

Color specification summary

	Intuitive	Perceptually uniform
RGB	✗	✗
HSL / HSV	✓	✗
CIE Lab	✗	✓
CIE LCh / HCL	✓	✓

45

Color use

46

Color use

Color maps

Semantics of color

Color blindness

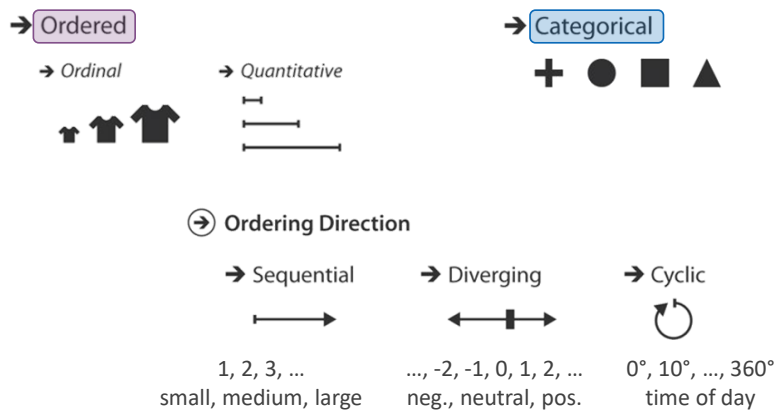
Importance of size

Relative perception

- Importance of contrast
- Importance of background
- Importance of surrounding color

Choosing colors

Data attributes



Color maps

Single variable

- Sequential color maps
- Diverging color maps
- Cyclic/circular color maps
- Categorical color maps

Two variables

- Bivariate color maps

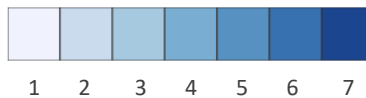
49

Sequential color maps

Desired properties

- Perceived differences correspond to value differences
- High discriminability

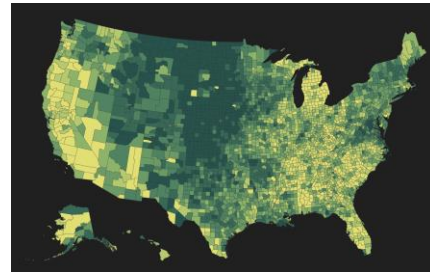
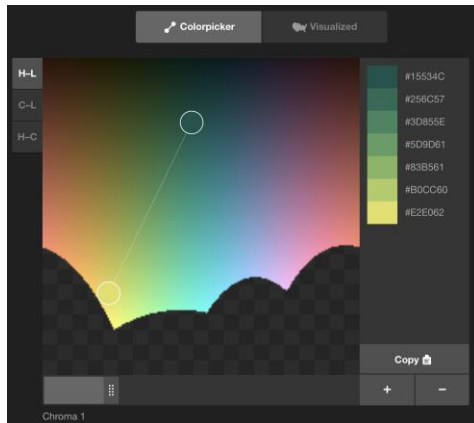
Single hue



Multi-hue



Sequential color maps



<http://tristen.ca/hcl-picker/>

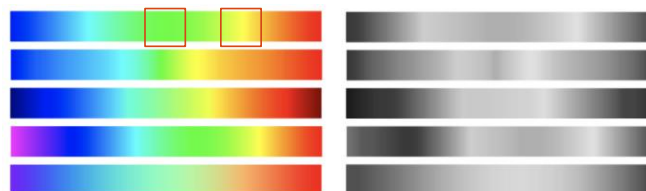
51

Sequential color maps: Rainbow

Overused because chosen as the default color map in many software packages

Issues

- Hue (that has no perceptual order) is used to indicate order
- Perceptual nonlinearity: divisions between hues create edges in visualization that have nothing to do with the data



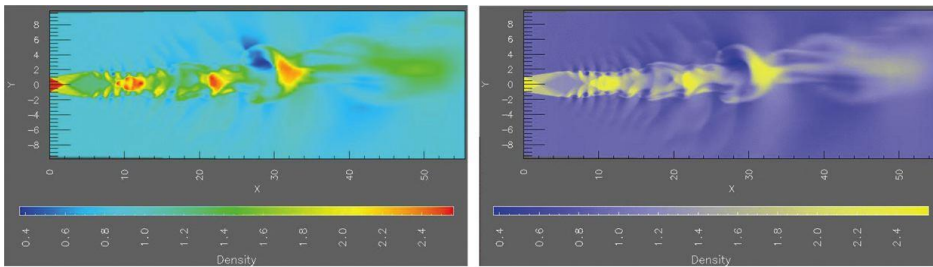
http://sci.utah.edu/~vdl/papers/2019_eurovis_implicit-discretization.pdf

52

Sequential color maps: Rainbow

Properties

- The details are harder to see
- Only advantage: Colors can be easily named

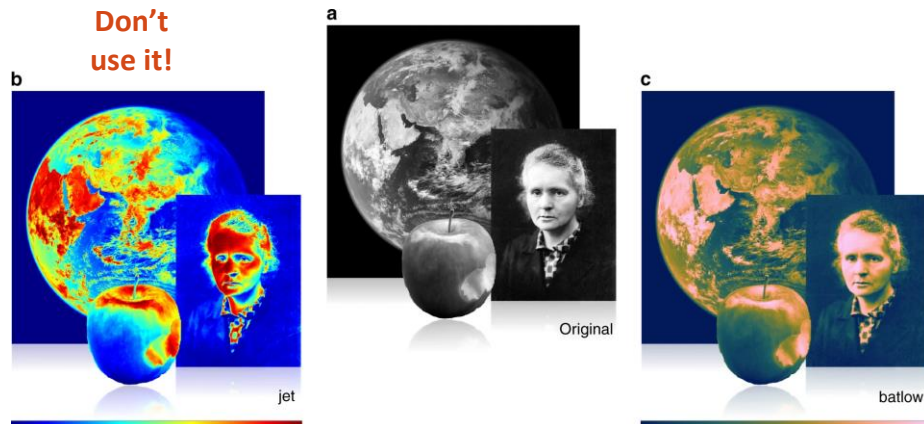


T. Munzner. *Visualization Analysis & Design*. CRC Press, Boca Raton, 2014

53

Sequential color maps: Rainbow

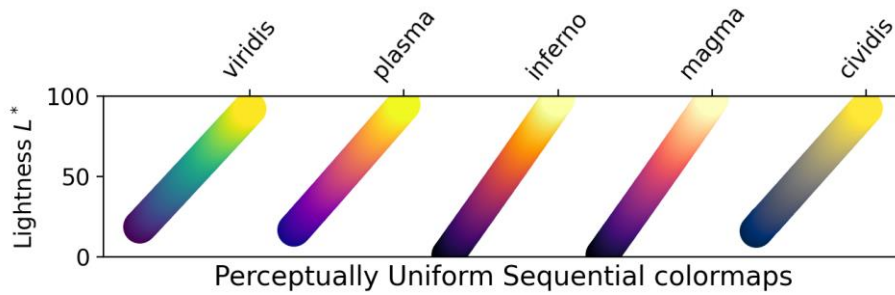
**Don't
use it!**



F. Crameri, G. E. Shephard, P. J. Heron. The misuse of colour in science communication. *Nature Communications*, 11: 5444, 2020

54

Perceptually linear sequential color maps



<https://matplotlib.org/stable/tutorials/colors/colormaps.html>

55

Diverging color maps

Encode two properties at the same time

- Above/below threshold (usually zero)
- Magnitude above/below threshold

Desired properties

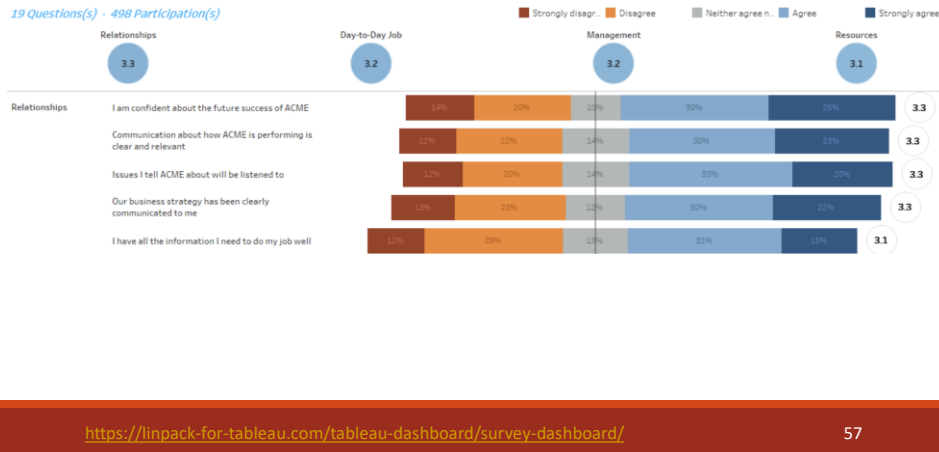
- Perceived differences correspond to value differences
- High discriminability
- Same luminance “ramp” on both sides



<http://colorbrewer2.org>

56

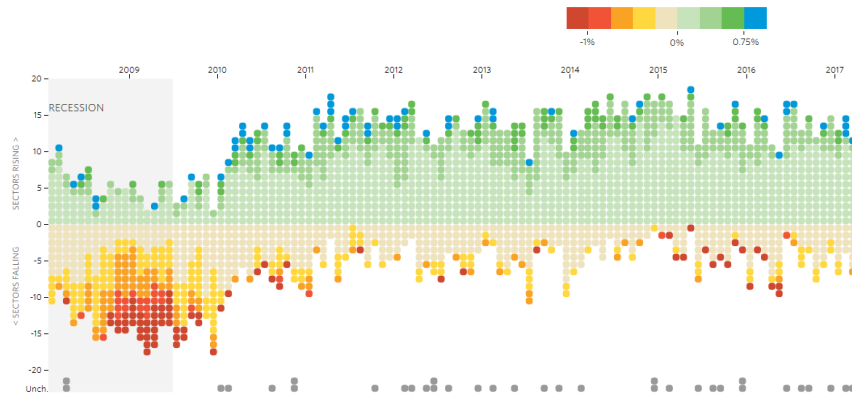
Diverging color maps – good example



Diverging color maps – bad example

Winners and Losers: Job Gains and Losses [Jump to National Unemployment](#)

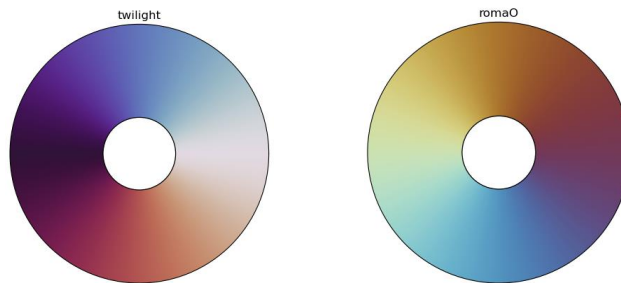
Track the number of sectors gaining or losing jobs each month. Boxes are shaded based on percentage change from the previous month in each sector's payrolls.



Cyclic/circular color maps

Desired properties

- Perceived differences correspond to value differences
- High discriminability
- Circular continuity (continuous transition between the highest and lowest values)



<https://www.fabiocrameri.ch/colourmaps/>

59

Categorical color maps

Desired properties

- Uniform saliency (nothing stands out)
- High discriminability



Use colors that can be named

Do not use too many different colors/categories

<http://colorbrewer2.org>

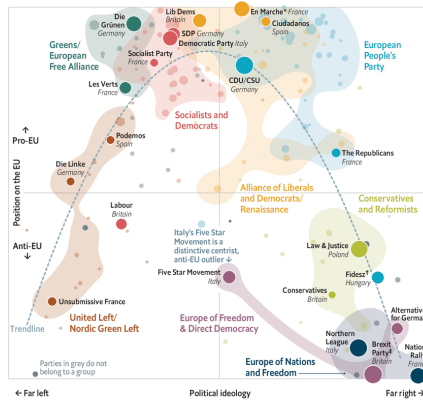
60

Categorical color maps

Anti-EU parties cluster at ideological extremes, whereas pro-EU ones are centrist

European Parliament political parties and groupings
By ideology and position on the EU

Party name — Parliamentary grouping 2019 election, provisional results, seats ○ 10 ○ 20



<https://www.economist.com/graphic-detail/2019/06/01/centrist-liberals-gained-the-most-power-in-the-eu-parliament>

Bivariate color maps

Binary



Categorical



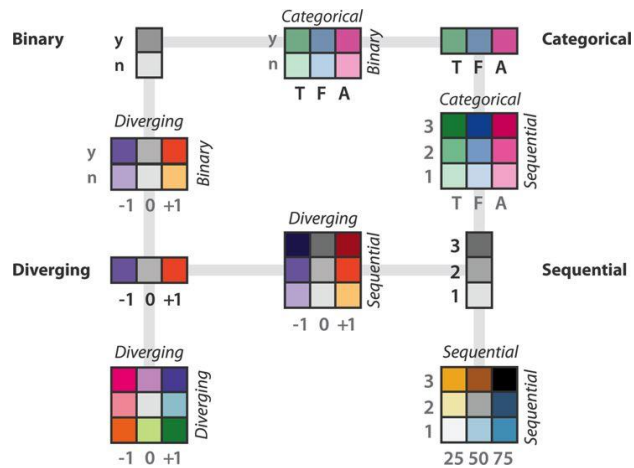
Diverging



Sequential



Bivariate color maps

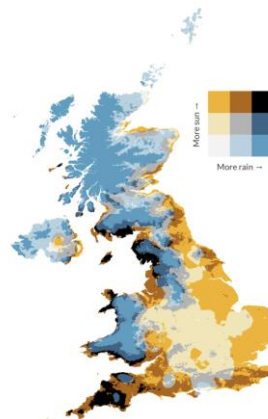


T. Munzner. *Visualization Analysis & Design*. CRC Press, Boca Raton, 2014

63

Bivariate color map example

The  and the 
Annual hours of sunshine vs. total precipitation in 2021



<https://github.com/VictimOfMaths/Maps/blob/master/SunvsRain.png>

64

Existing color maps

Number of data classes: 5

Nature of your data: sequential diverging qualitative

Pick a color scheme:

Only show: colorblind safe print friendly photocopy safe

Context: roads cities borders

Background: solid color terrain

ColorBrewer 2.0
color advice for cartography

5-class Set1

HEX: #e41a1c, #377eb8, #4daf4a, #984ea3, #ff7f00

<http://colorbrewer2.org>

65

Existing color maps

Sequential gradients

Diverging gradients

Cyclic gradients

Continuous palettes

Discrete palettes

Category palettes

Perceptually uniform
Perceptually ordered
Colour-vision deficiency friendly
Readable in black&white

Widely compatible
Accessible and free
Versioned & citable

By the community, for the community.

www.fabiocrameri.ch/colourmaps/

Scientific

<https://www.fabiocrameri.ch/colourmaps/>

66

Custom color maps

3 Check and configure the resulting palette

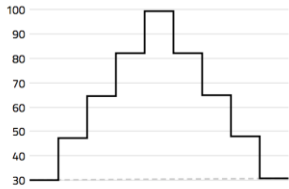
✓ This palette is colorblind-safe.

correct lightness bezier interpolation

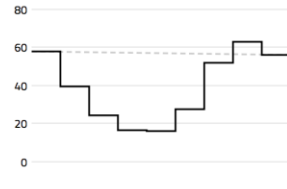
simulate: normal deut. prot. trit.



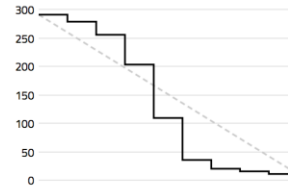
lightness



saturation



hue



<https://gka.github.io/palettes/>

67

Custom color maps

VIZ PALETTE By: Elijah Meeks & Susie Lu

COLORS IN ACTION

Font color: #000000
Charts made with Semiotic

PICK

Use Chromajs

Use Colorgorical

Use ColorBrewer

EDIT

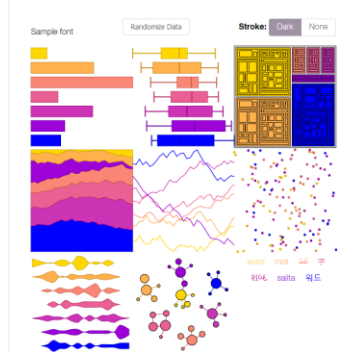
1 #4169e1 ✕
2 #4169e1 ✕
3 #4169e1 ✕
4 #4169e1 ✕
5 #4169e1 ✕
6 #4169e1 ✕
7 #4169e1 ✕

GET

String quotes
 Object with metadata
["#4169e1", "#4169e1", "#4169e1", "#4169e1", "#4169e1", "#4169e1", "#4169e1"]
@hex Orig
@hex

Color Population:

No Color Deficiency - 99% Deuteranomaly - 2.7% Protanomaly - 0.66%
Protanopia - 0.59% Deuteranopia - 0.56%



<https://projects.susielu.com/viz-palette>

68

Semantics of color

Green = good

Red = bad

Gray perceived as “no color”

- Missing data
- Uncategorized data
- Non-emphasized data

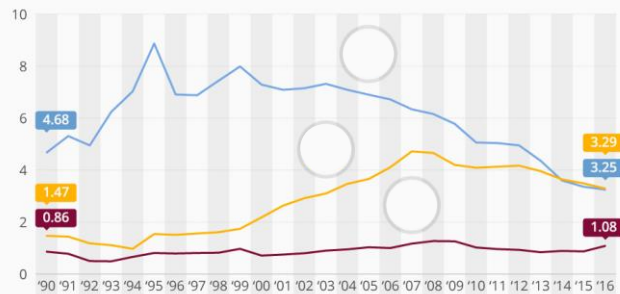
Very powerful when used appropriately

69

Semantics of color

Russians Are Turning Their Backs On Vodka

Liters of pure alcohol consumed per capita in Russia by beverage



© StatistaCharts Source: World Health Organization

statista

<https://www.statista.com/chart/15918/liters-of-pure-alcohol-consumed-per-capita-in-russia/>

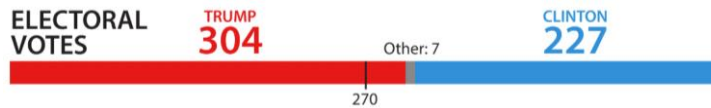
70

Semantics of color

Use color consistently

Example from US politics

- Republicans = red
- Democrats = blue

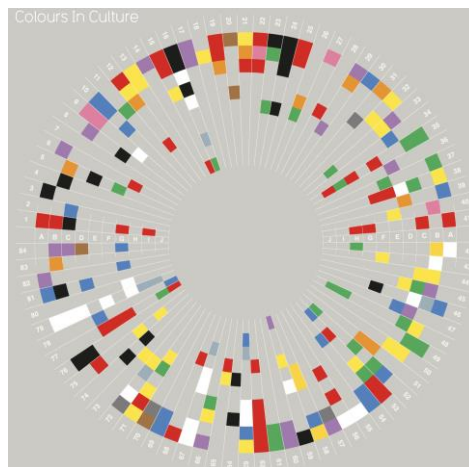


71

Semantics of color

Meaning changes depending on culture

- A Western / American
- B Japanese
- C Hindu
- D Native American
- E Chinese
- F Asian
- G Eastern European
- H Arab
- I African
- J South American



<https://informationisbeautiful.net/visualizations/colours-in-cultures/>

72

Semantics of color

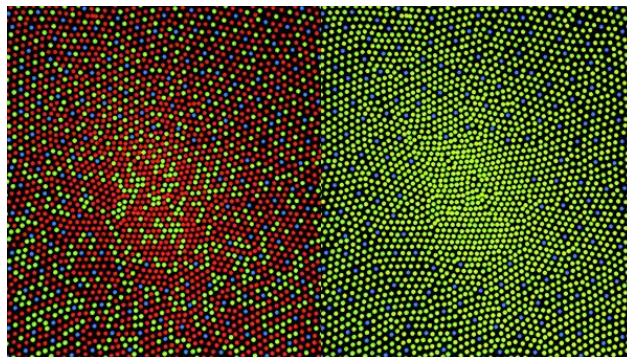
Floor of a
children's
hospital



73

Color blindness

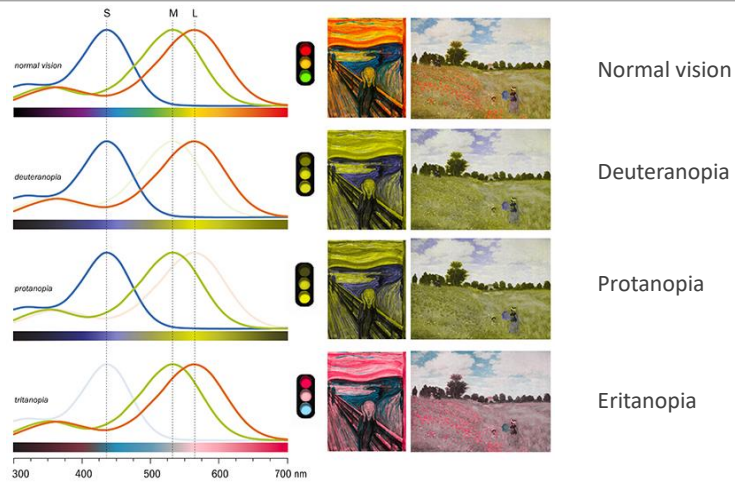
Red-green color blindness affects up to 8% of males and 0.5% of females of Northern European descent



https://en.wikipedia.org/wiki/Color_blindness

74

Color blindness

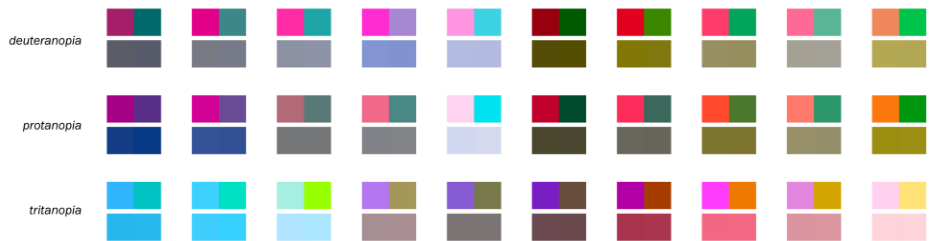


<http://mkweb.bcgsc.ca/colorblind/>

75

Color blindness

indistinguishable colors in color blindness

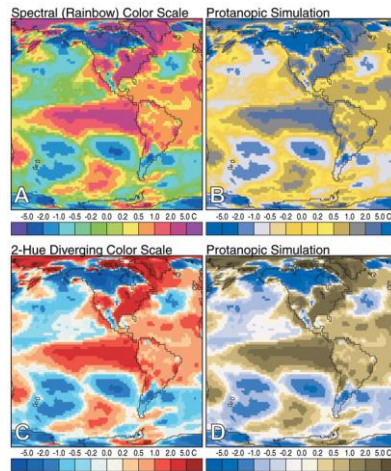


<http://mkweb.bcgsc.ca/colorblind/>

<http://mkweb.bcgsc.ca/colorblind/>

76

Color blindness



<https://visual.ly/blog/rainbow-color-scales/>

77

Color blindness

Color	Color name	RGB (1–255)	CMYK (%)	P	D
	Black	0, 0, 0	0, 0, 0, 100		
	Orange	230, 159, 0	0, 50, 100, 0		
	Sky blue	86, 180, 233	80, 0, 0, 0		
	Bluish green	0, 158, 115	97, 0, 75, 0		
	Yellow	240, 228, 66	10, 5, 90, 0		
	Blue	0, 114, 178	100, 50, 0, 0		
	Vermillion	213, 94, 0	0, 80, 100, 0		
	Reddish purple	204, 121, 167	10, 70, 0, 0		

Wong, B. (2011) Points of view: Color blindness. *Nature Methods* 8:441.

See also tools from <https://www.color-blindness.com/2008/12/23/15-tools-color-blindness/>

<http://mkweb.bcgsc.ca/colorblind/>

78

Color blindness – use tools to check

3 Check and configure the resulting palette

correct lightness
 bezier interpolation

This palette is colorblind-safe.

 simulate: normal deut. prot. trit.

<https://gka.github.io/palettes/>
79

Color blindness – use tools to check

VIZ PALETTE

By: Elijah Meeks & Susie Lu

PICK

Use Chromajs

Use ColorBrewer

EDIT

- 1 #4169b1
- 2 #4169b1
- 3 #4169b1
- 4 #4169b1
- 5 #4169b1
- 6 #4169b1
- 7 #4169b1

GET

```
[{"x": 1, "y": 1}, {"x": 2, "y": 2}, {"x": 3, "y": 3}, {"x": 4, "y": 4}, {"x": 5, "y": 5}, {"x": 6, "y": 6}, {"x": 7, "y": 7}, {"x": 8, "y": 8}, {"x": 9, "y": 9}, {"x": 10, "y": 10}, {"x": 11, "y": 11}, {"x": 12, "y": 12}, {"x": 13, "y": 13}, {"x": 14, "y": 14}, {"x": 15, "y": 15}, {"x": 16, "y": 16}, {"x": 17, "y": 17}, {"x": 18, "y": 18}, {"x": 19, "y": 19}, {"x": 20, "y": 20}, {"x": 21, "y": 21}, {"x": 22, "y": 22}, {"x": 23, "y": 23}, {"x": 24, "y": 24}, {"x": 25, "y": 25}, {"x": 26, "y": 26}, {"x": 27, "y": 27}, {"x": 28, "y": 28}, {"x": 29, "y": 29}, {"x": 30, "y": 30}, {"x": 31, "y": 31}, {"x": 32, "y": 32}, {"x": 33, "y": 33}, {"x": 34, "y": 34}, {"x": 35, "y": 35}, {"x": 36, "y": 36}, {"x": 37, "y": 37}, {"x": 38, "y": 38}, {"x": 39, "y": 39}, {"x": 40, "y": 40}, {"x": 41, "y": 41}, {"x": 42, "y": 42}, {"x": 43, "y": 43}, {"x": 44, "y": 44}, {"x": 45, "y": 45}, {"x": 46, "y": 46}, {"x": 47, "y": 47}, {"x": 48, "y": 48}, {"x": 49, "y": 49}, {"x": 50, "y": 50}, {"x": 51, "y": 51}, {"x": 52, "y": 52}, {"x": 53, "y": 53}, {"x": 54, "y": 54}, {"x": 55, "y": 55}, {"x": 56, "y": 56}, {"x": 57, "y": 57}, {"x": 58, "y": 58}, {"x": 59, "y": 59}, {"x": 60, "y": 60}, {"x": 61, "y": 61}, {"x": 62, "y": 62}, {"x": 63, "y": 63}, {"x": 64, "y": 64}, {"x": 65, "y": 65}, {"x": 66, "y": 66}, {"x": 67, "y": 67}, {"x": 68, "y": 68}, {"x": 69, "y": 69}, {"x": 70, "y": 70}, {"x": 71, "y": 71}, {"x": 72, "y": 72}, {"x": 73, "y": 73}, {"x": 74, "y": 74}, {"x": 75, "y": 75}, {"x": 76, "y": 76}, {"x": 77, "y": 77}, {"x": 78, "y": 78}, {"x": 79, "y": 79}, {"x": 80, "y": 80}, {"x": 81, "y": 81}, {"x": 82, "y": 82}, {"x": 83, "y": 83}, {"x": 84, "y": 84}, {"x": 85, "y": 85}, {"x": 86, "y": 86}, {"x": 87, "y": 87}, {"x": 88, "y": 88}, {"x": 89, "y": 89}, {"x": 90, "y": 90}, {"x": 91, "y": 91}, {"x": 92, "y": 92}, {"x": 93, "y": 93}, {"x": 94, "y": 94}, {"x": 95, "y": 95}, {"x": 96, "y": 96}, {"x": 97, "y": 97}, {"x": 98, "y": 98}, {"x": 99, "y": 99}, {"x": 100, "y": 100}
        
```

COLORS IN ACTION

Font color: #000000

Charts made with Semiotic

Color Population:

- No Color Deficiency - 99%
- Deuteranomaly - 2.7%
- Protanomaly - 0.66%
- Protanopia - 0.59%
- Deuteranopia - 0.56%

<https://projects.susielu.com/viz-palette>
80

Color blindness

Use colorblind safe palettes

Blue/orange and blue/red normally safe

Test design with color blindness simulators

If you really need to use red/green, make sure they vary in lightness



Normal vision



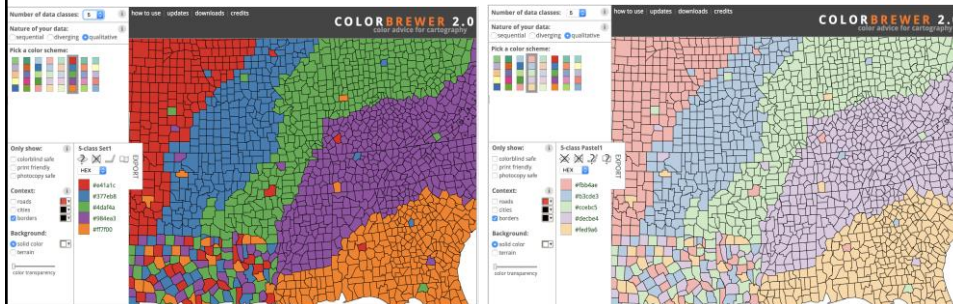
Deuteranopia

Importance of size

Small size hurts discriminability

Small area high saturation

Large area low saturation



Relative perception

Our color perception is not absolute, but relative

- Importance of contrast
- Importance of background
- Importance of surrounding color

83

Importance of contrast

CONTRAST RATIOS

1.0				
1.1	Choose if you dislike readers.	That's bad.	That's bad.	Horrible.
1.5	Ok in 1% of the cases.	Not ideal.	That's bad.	My eyes!
2.5	Can be a good choice.	Ok.	Not ideal.	That's bad.
4.5	Safe choice.	Great.	Ok.	Not ideal.

Contrast is most easily changed using luminance/lightness

<https://blog.datawrapper.de/colors/>

84

Importance of contrast

Colour Contrast Check

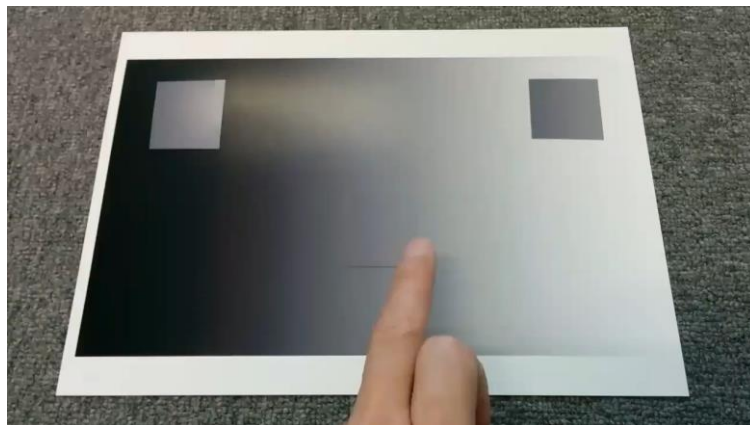
Date created: January 11, 2005
Date last modified: January 11, 2015

Foreground Colour:	Background Colour:	Results
# 63BD7B	# 8DE7E7	This is example text. Some of it bolded . Some of it <i>italicized</i> .
Red: <input type="text"/>	Red: <input type="text"/>	Brightness Difference: (>= 125) <input type="text" value="49.524"/>
Green: <input type="text"/>	Green: <input type="text"/>	Colour Difference: (>= 500) <input type="text" value="192"/>
Blue: <input type="text"/>	Blue: <input type="text"/>	Are colours compliant? <input type="text" value="NO"/>
Hue (°): <input type="text"/>	Hue (°): <input type="text"/>	Contrast Ratio <input type="text" value="1.618"/>
Saturation (%): <input type="text"/>	Saturation (%): <input type="text"/>	WCAG 2 AA Compliant <input type="text" value="NO"/>
Value (%): <input type="text"/>	Value (%): <input type="text"/>	WCAG 2 AA Compliant (18pt+) <input type="text" value="NO"/>
		WCAG 2 AAA Compliant <input type="text" value="NO"/>
		WCAG 2 AAA Compliant (18pt+) <input type="text" value="NO"/>

https://snook.ca/technical/colour_contrast/colour.html#fg=63BD7B,bg=8DE7E7

85

Importance of background



<https://twitter.com/AkiyoshiKitaoka/status/1028473566193315841>

86

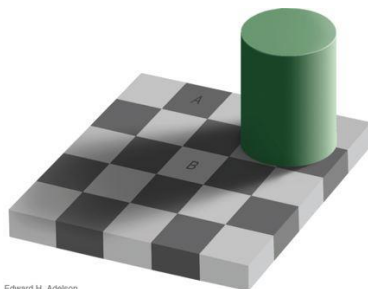
Importance of background



<https://www.rtvsllo.si/zdravje/novi-koronavirus/svetovalna-skupina-priporoca-tretji-odmerek-za-starejse-od-70-let-in-kronicne-bolnike/592726>

87

Importance of surrounding color



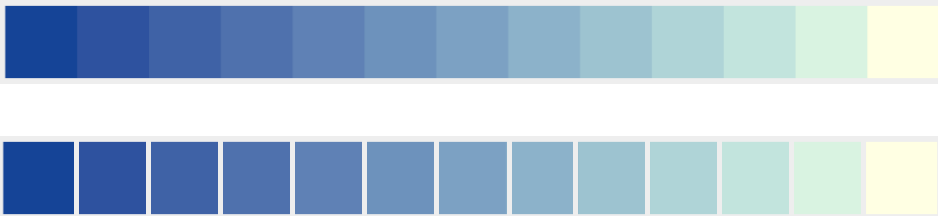
Edward H. Adelson

T. Munzner. *Visualization Analysis & Design*. CRC Press, Boca Raton, 2014

88

Importance of surrounding color

Mach bands



89

Importance of surrounding color

Our interpretation of colors is based on our expectations

Color constancy

- A feature of human color perception
- Ensures that the perceived color remains relatively constant under varying illumination conditions
- Helps us to identify objects

Strawberries appear to be red although the pixels are not



<http://www.psy.ritsumei.ac.jp/~akitaoka/strawberries-color-constancy2017e.pdf>

90

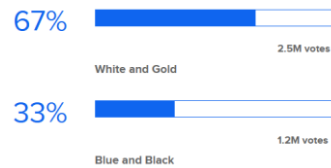
Importance of surrounding color

“The dress”



What colors are this dress?

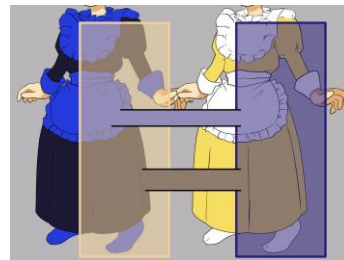
- White and gold
- Blue and black



<https://www.buzzfeed.com/catesish/help-am-i-going-insane-its-definitely-blue#subbuzz-quiz-poll-results-5103755>

Importance of surrounding color

“The dress”



Theory: Image overexposed, color interpretation depends on our interpretation of the lighting

- Background lightning → White and gold
- Frontal lightning → Blue and black

https://en.wikipedia.org/wiki/The_dress

Importance of surrounding color

“The dress”



The rabbit-duck illusion



https://en.wikipedia.org/wiki/The_dress

https://en.wikipedia.org/wiki/Rabbit%E2%80%93duck_illusion

93

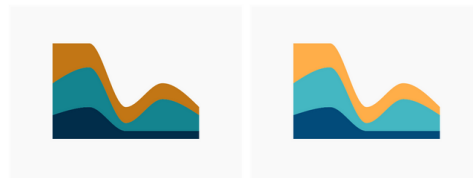
Choosing colors

Use the right amount of contrast to the background



NOT IDEAL

BETTER



NOT IDEAL

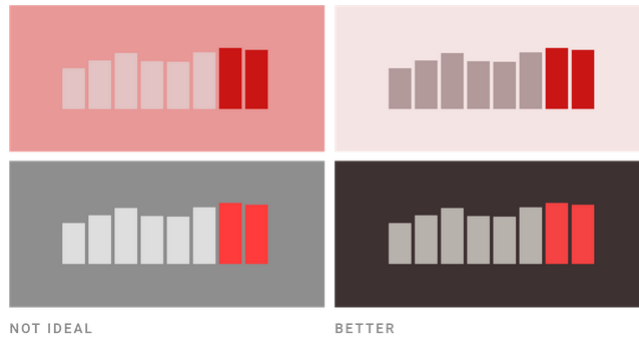
BETTER

<https://blog.datawrapper.de/beautifulcolors/>

94

Choosing colors

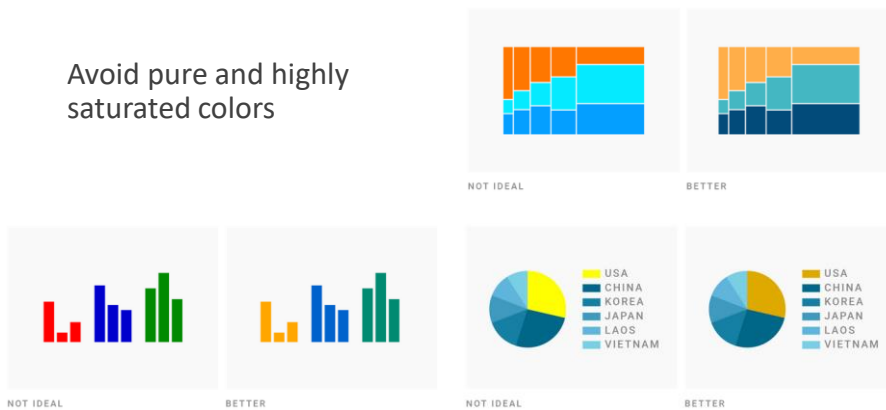
Background should not be too saturated



<https://blog.datawrapper.de/beautifulcolors/>

Choosing colors

Avoid pure and highly saturated colors



<https://blog.datawrapper.de/beautifulcolors/>

Color use summary

Use color sparingly

Use color consistently

Be thoughtful of the tone that color conveys

- Enforce emotions
- Consider culture

Design with colorblind in mind

Keep in mind that our perception is relative (the effect of contrast, background color and surrounding color)

Color use summary

Colorbrewer is your friend!

Stay away from the rainbow!

