

Rainbows & Research

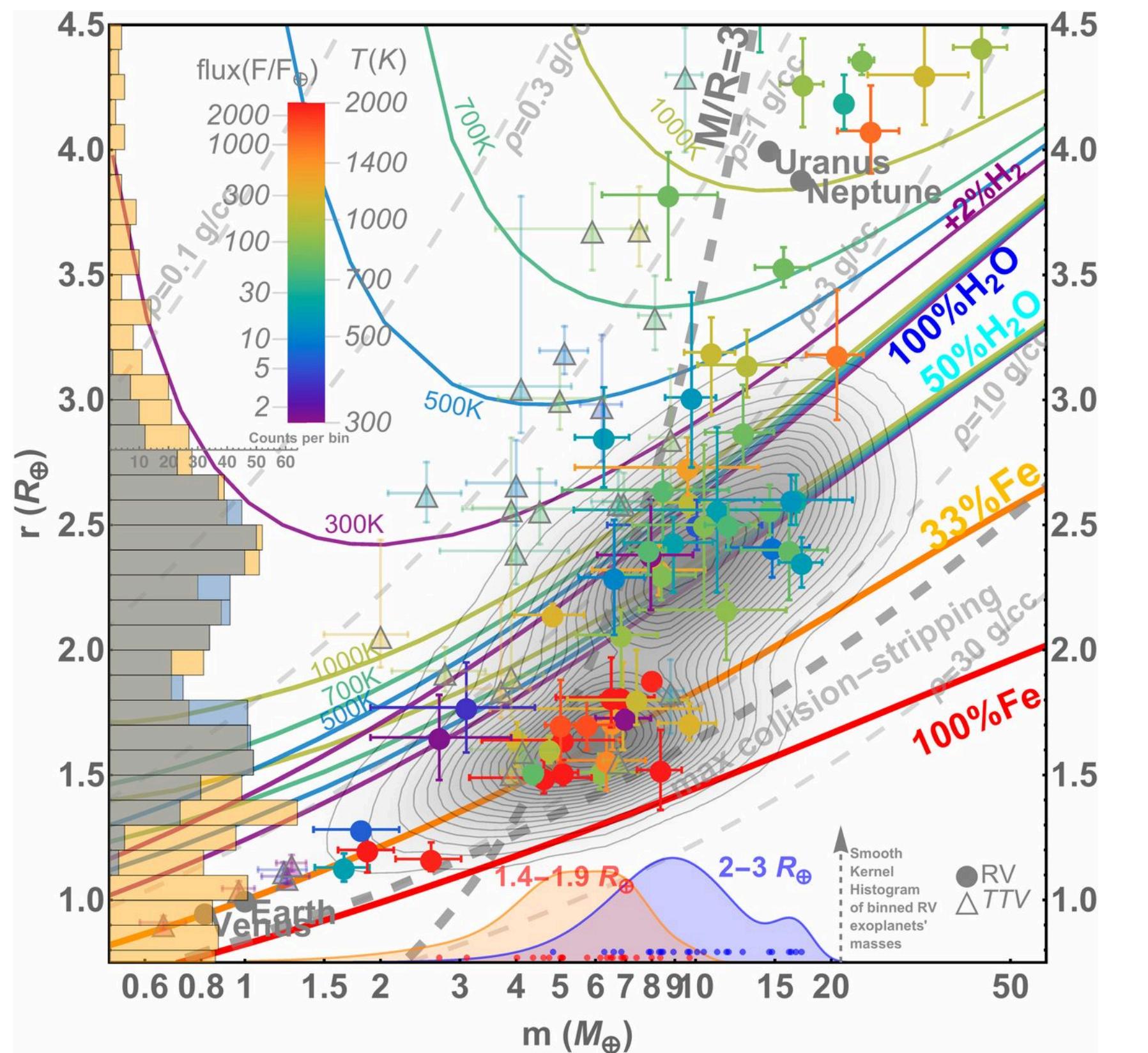
The Science of Color Palettes

Marc Schlichting, May-The-Fourth-Be-With-You Day 2024



Clothes make the man.

Popular German Novella by Gottfried Keller



Zeng et al. (2019)



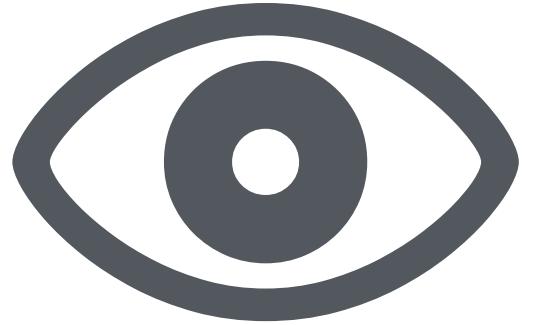
Clothes make the man.

Popular German Novella by Gottfried Keller

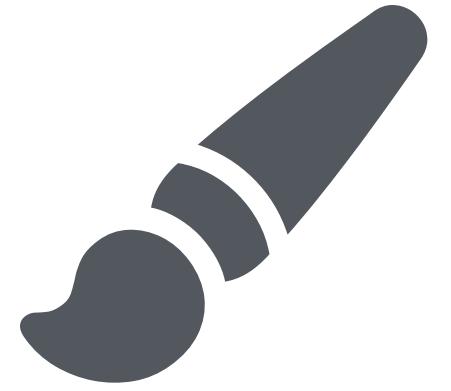
Color Palette Criteria



Distinguishable



Accessible



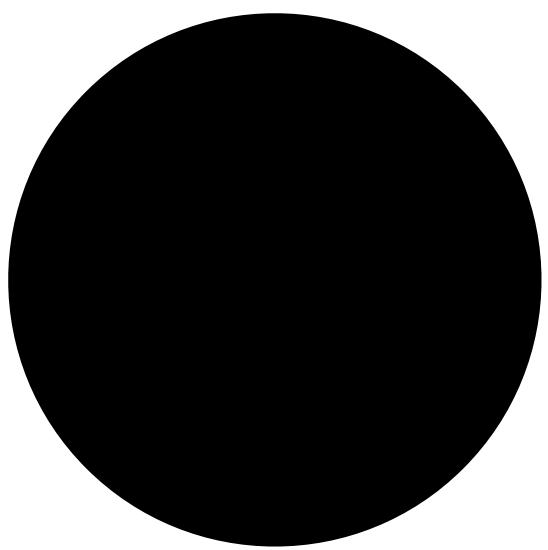
Aesthetic

Distinguishability

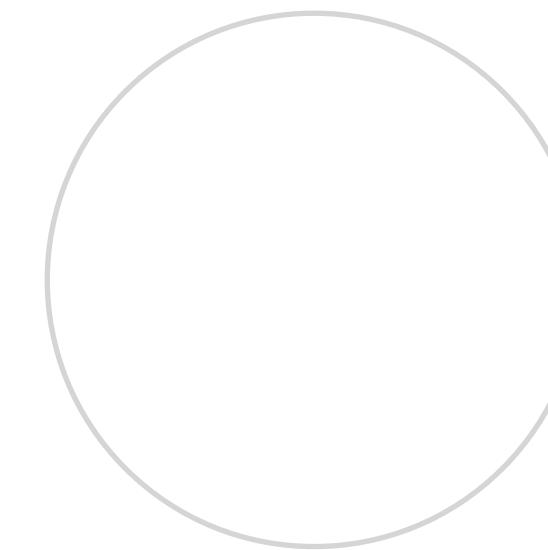
RGB Colorspace

(R,G,B)

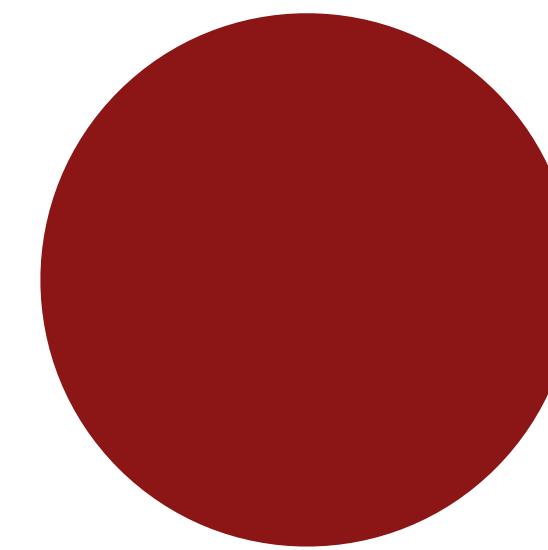
Additive Colorspace



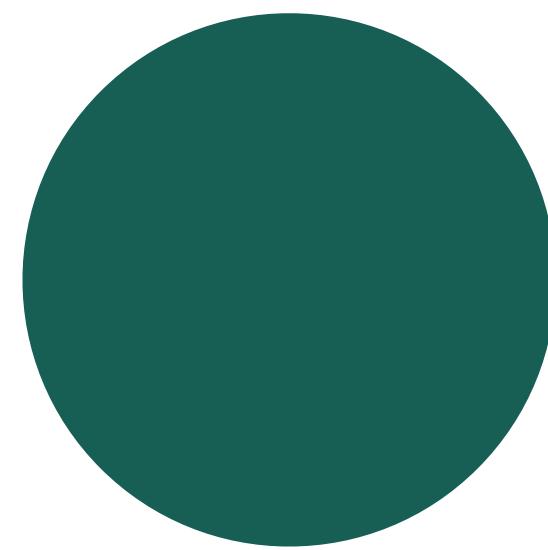
(0,0,0)



(1,1,1)

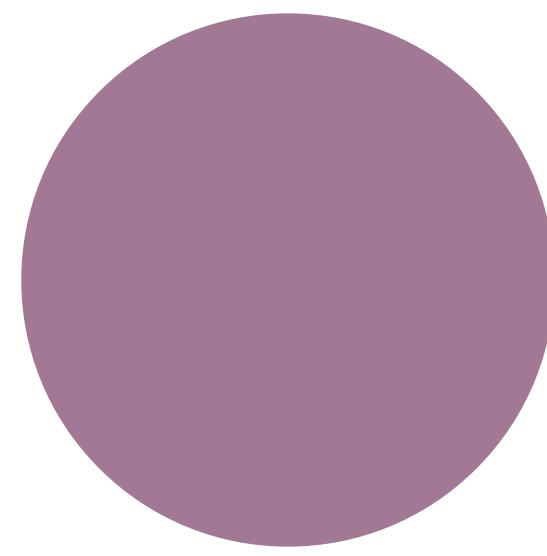


(0.55,0.08,0.08)

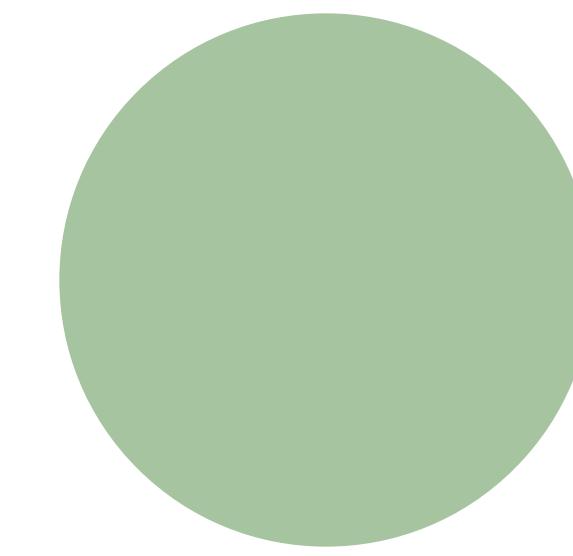


(0.09,0.37,0.33)

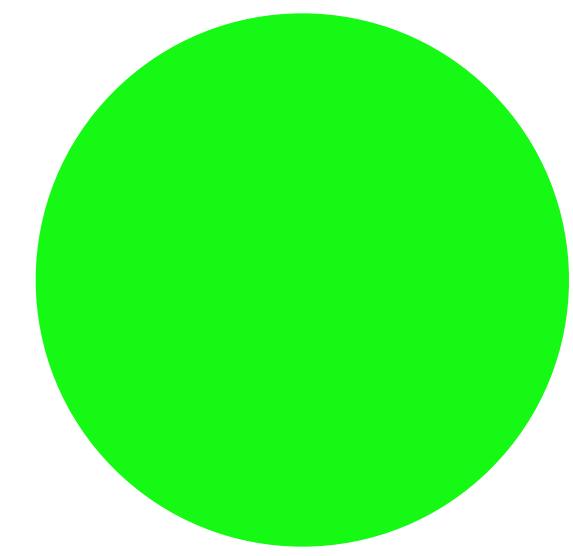
Distance in RGB Colorspace



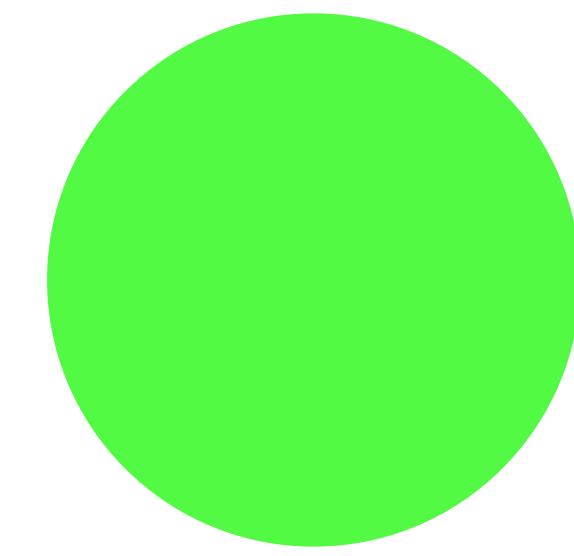
$$c_1 = (0.64, 0.47, 0.58)$$



$$c_2 = (0.65, 0.77, 0.63)$$



$$c_3 = (0.09, 0.98, 0.08)$$



$$c_4 = (0.32, 0.98, 0.27)$$

$$\|c_1 - c_2\|_2 = 0.3$$

$$\|c_3 - c_4\|_2 = 0.3$$

Takeaway: Euclidean distances in RGB are \neq perceptual distances

LAB Colorspace

(L,a,b)



0

100

L



-128

a



-128

b

127

127

Delta E Color Distance

Delta E 76

$$\Delta E = \sqrt{(L_2 - L_1)^2 + (a_2 - a_1)^2 + (b_2 - b_1)^2}$$

Unfortunately: Even the LAB colorspace is not perceptually uniform

Delta E Color Distance

Delta E 94

$$\Delta E_{94}^* = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C_{ab}^*}{k_C S_C}\right)^2 + \left(\frac{\Delta H_{ab}^*}{k_H S_H}\right)^2}$$

$$\Delta L^* = L_1^* - L_2^*$$

$$C_1^* = \sqrt{a_1^{*2} + b_1^{*2}}$$

$$C_2^* = \sqrt{a_2^{*2} + b_2^{*2}}$$

$$\Delta C_{ab}^* = C_1^* - C_2^*$$

$$\Delta H_{ab}^* = \sqrt{{\Delta E_{ab}^*}^2 - {\Delta L^*}^2 - {\Delta C_{ab}^*}^2} = \sqrt{{\Delta a^*}^2 + {\Delta b^*}^2 - {\Delta C_{ab}^*}^2}$$

$$\Delta a^* = a_1^* - a_2^*$$

$$\Delta b^* = b_1^* - b_2^*$$

$$S_L = 1$$

$$S_C = 1 + K_1 C_1^*$$

$$S_H = 1 + K_2 C_1^*$$

Still not good enough...apparently

Delta E Color Distance

Delta E 2000

$$\Delta E_{00}^* = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_C S_C}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C} \frac{\Delta H'}{k_H S_H}}$$

$$\Delta L' = L_2^* - L_1^*$$

$$\bar{L} = \frac{L_1^* + L_2^*}{2} \quad \bar{C} = \frac{C_1^* + C_2^*}{2}$$

$$a'_1 = a_1^* + \frac{a_1^*}{2} \left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right) \quad a'_2 = a_2^* + \frac{a_2^*}{2} \left(1 - \sqrt{\frac{\bar{C}^7}{\bar{C}^7 + 25^7}}\right)$$

$$\bar{C}' = \frac{C'_1 + C'_2}{2} \text{ and } \Delta C' = C'_2 - C'_1 \quad \text{where } C'_1 = \sqrt{a'^2_1 + b'^2_1} \quad C'_2 = \sqrt{a'^2_2 + b'^2_2}$$

$$h'_1 = \text{atan2}(b_1^*, a'_1) \mod 360^\circ, \quad h'_2 = \text{atan2}(b_2^*, a'_2) \mod 360^\circ$$

$$\Delta h' = \begin{cases} h'_2 - h'_1 & |h'_1 - h'_2| \leq 180^\circ \\ h'_2 - h'_1 + 360^\circ & |h'_1 - h'_2| > 180^\circ, h'_2 \leq h'_1 \\ h'_2 - h'_1 - 360^\circ & |h'_1 - h'_2| > 180^\circ, h'_2 > h'_1 \end{cases}$$

$$\Delta H' = 2\sqrt{C'_1 C'_2} \sin(\Delta h'/2), \quad \bar{H}' = \begin{cases} (h'_1 + h'_2 + 360^\circ)/2 & |h'_1 - h'_2| > 180^\circ \\ (h'_1 + h'_2)/2 & |h'_1 - h'_2| \leq 180^\circ \end{cases}$$

$$T = 1 - 0.17 \cos(\bar{H}' - 30^\circ) + 0.24 \cos(2\bar{H}') + 0.32 \cos(3\bar{H}' + 6^\circ) - 0.20 \cos(4\bar{H}' - 63^\circ)$$

$$S_L = 1 + \frac{0.015 (\bar{L} - 50)^2}{\sqrt{20 + (\bar{L} - 50)^2}} \quad S_C = 1 + 0.045 \bar{C}' \quad S_H = 1 + 0.015 \bar{C}' T$$

$$R_T = -2 \sqrt{\frac{\bar{C}'^7}{\bar{C}'^7 + 25^7}} \sin \left[60^\circ \cdot \exp \left(- \left[\frac{\bar{H}' - 275^\circ}{25^\circ} \right]^2 \right) \right]$$

We still use this today...so hopefully good enough

Delta E Color Distance

Delta E 2000

Delta E**Perception**

< 1

Not distinguishable by humans

1 - 2

Difference can only be seen through close observation

2 - 10

Distinguishable

11 - 49

Colors are more similar than opposite

100

Colors are the exact opposite

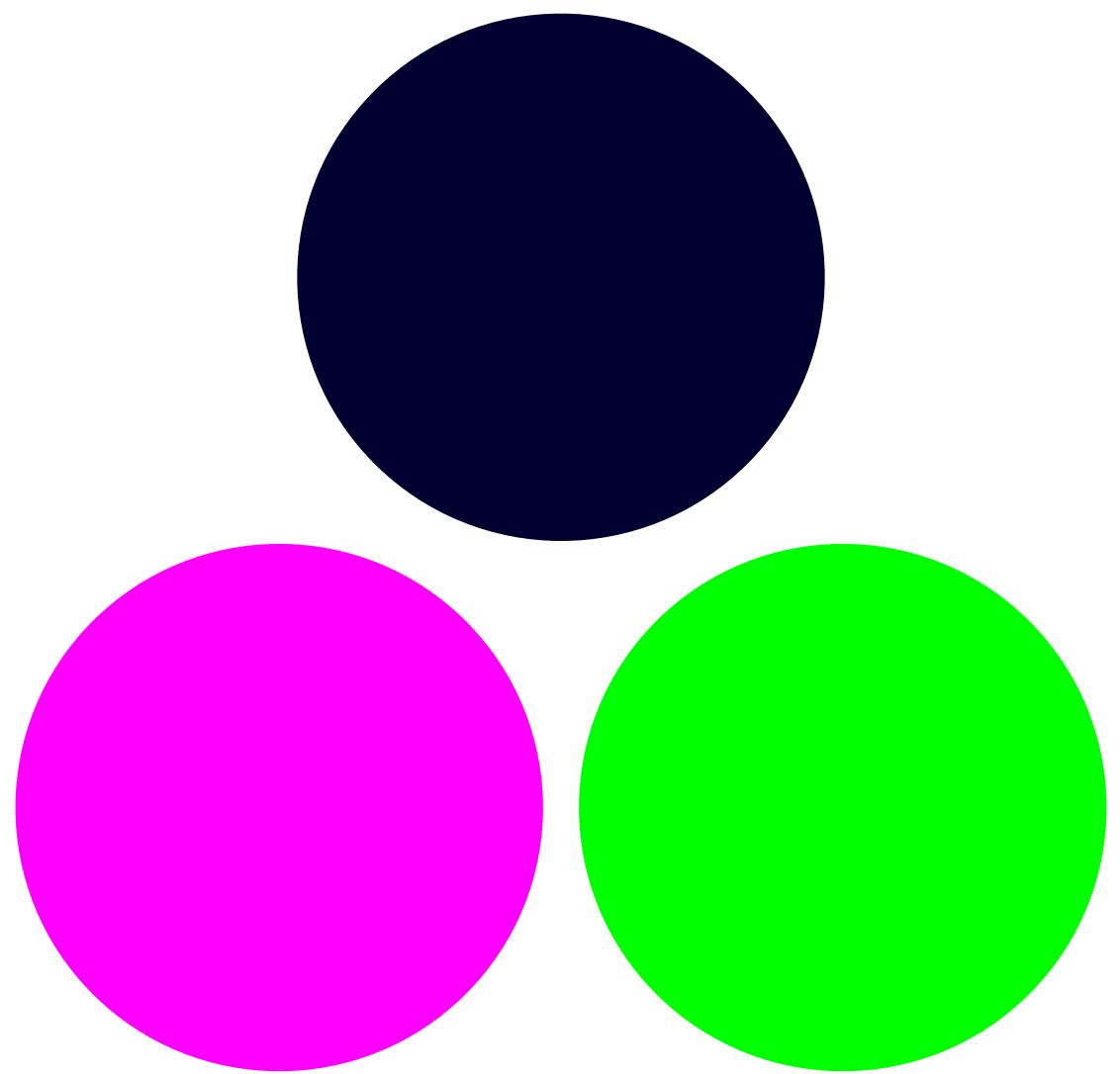
The Perfect Color Palette

A First Attempt

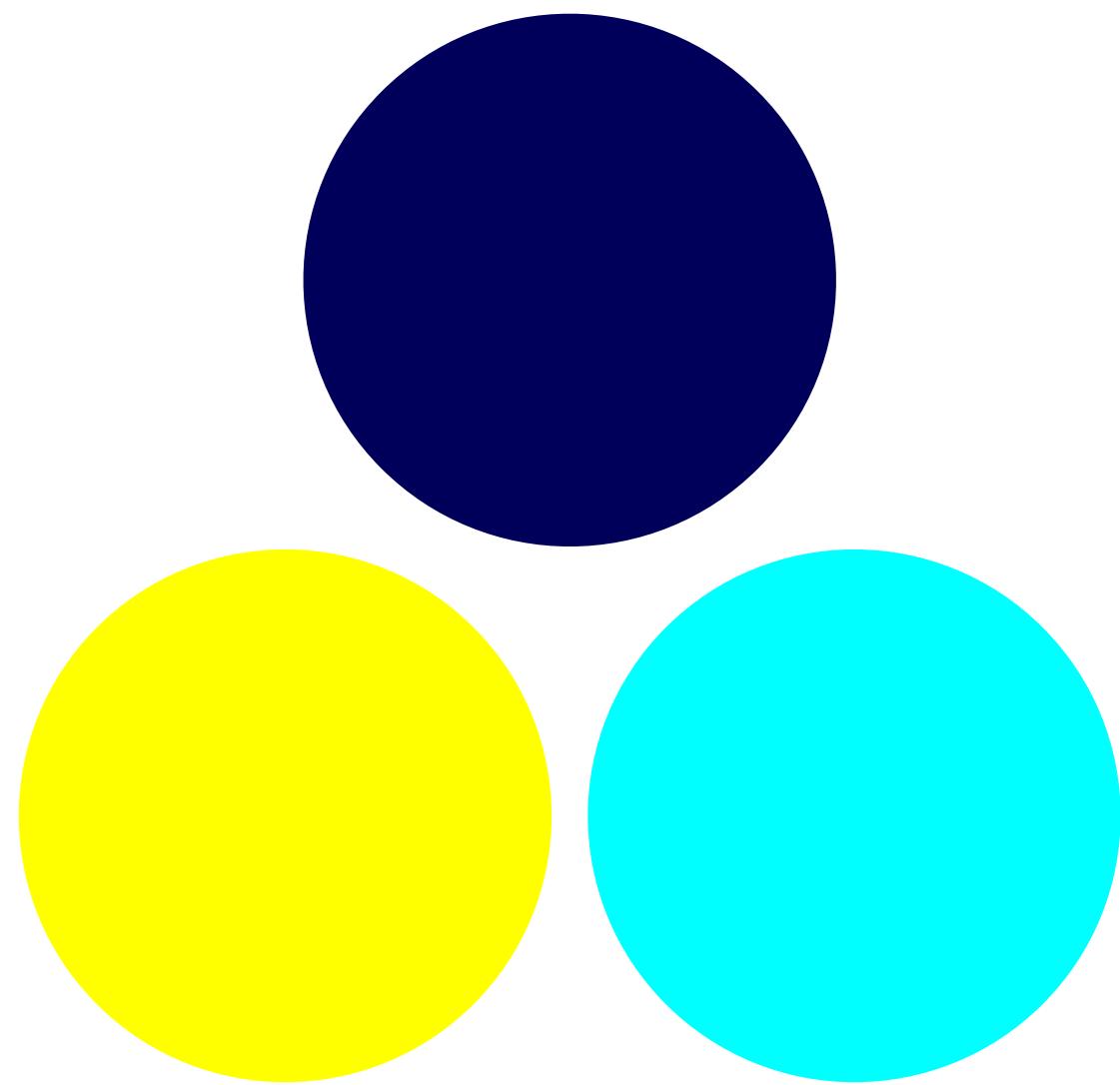
$$\underset{c_1, \dots, c_n}{\text{maximize}} \sum_{i=1}^{n-1} \left(\sum_{j=i+1}^n (\Delta E(c_i, c_j)) \right)$$

The Perfect Color Palette

A First Attempt



Mode 1



Mode 2

Especially mode 2 is visually hard to distinguish from a white background

The Perfect Color Palette

A Second Attempt

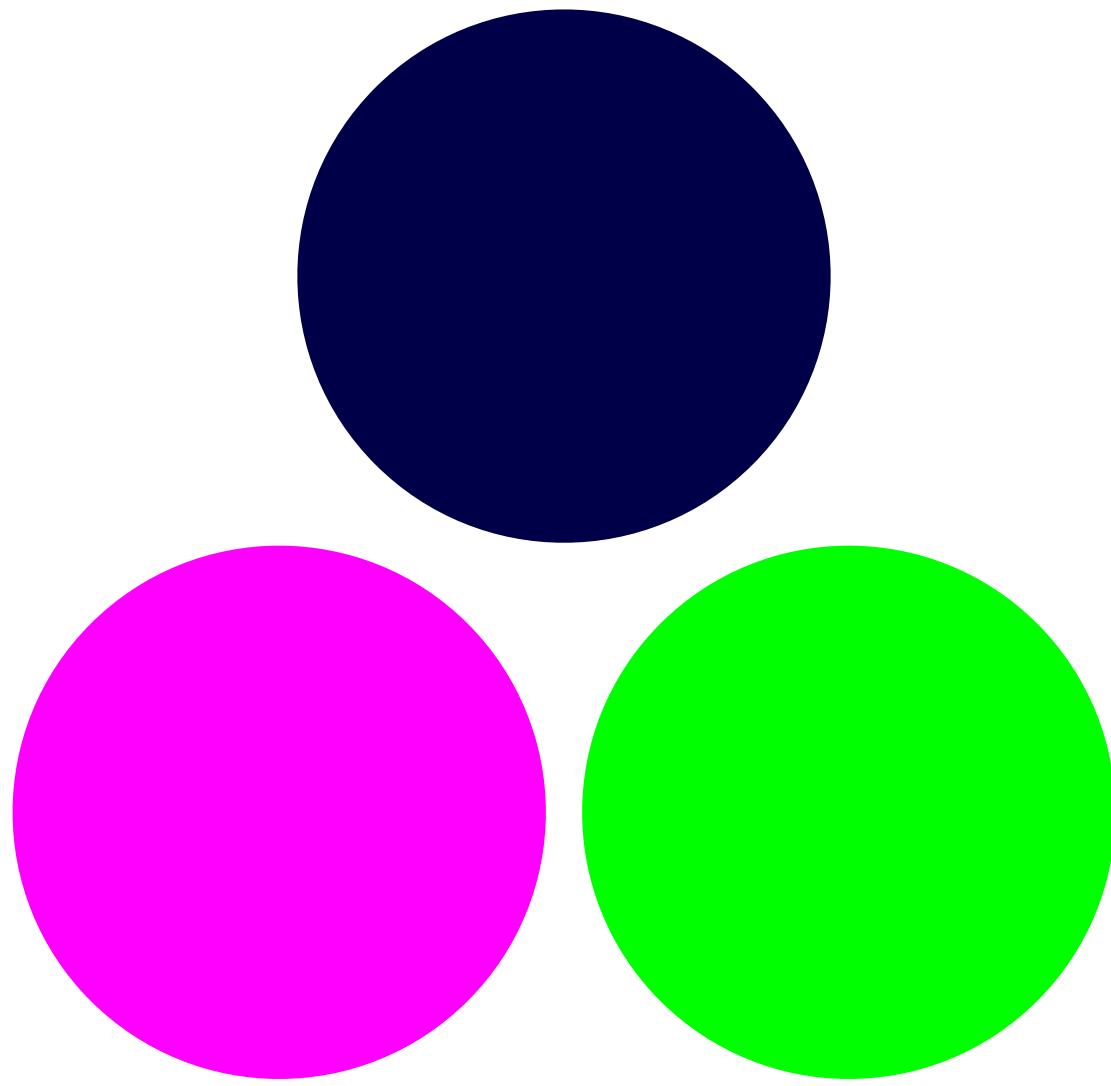
$$\underset{c_1, \dots, c_n}{\text{maximize}} \sum_{i=1}^{n-1} \left(\sum_{j=i+1}^n (\Delta E(c_i, c_j)) \right) + \sum_{i=1}^n (\Delta E(c_0, c_i))$$



Background Color

The Perfect Color Palette

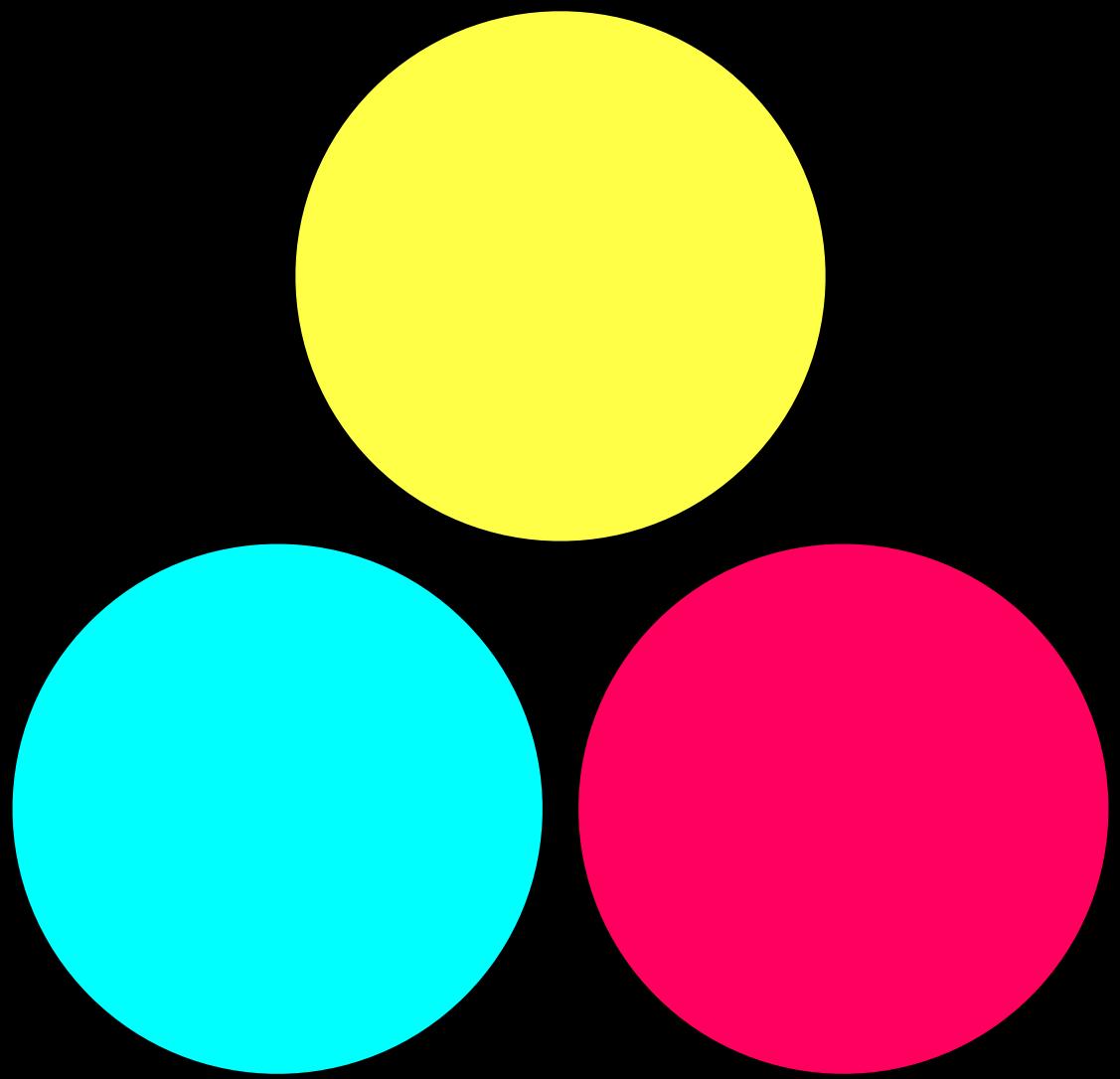
A Second Attempt



Mode 1

The Perfect Color Palette

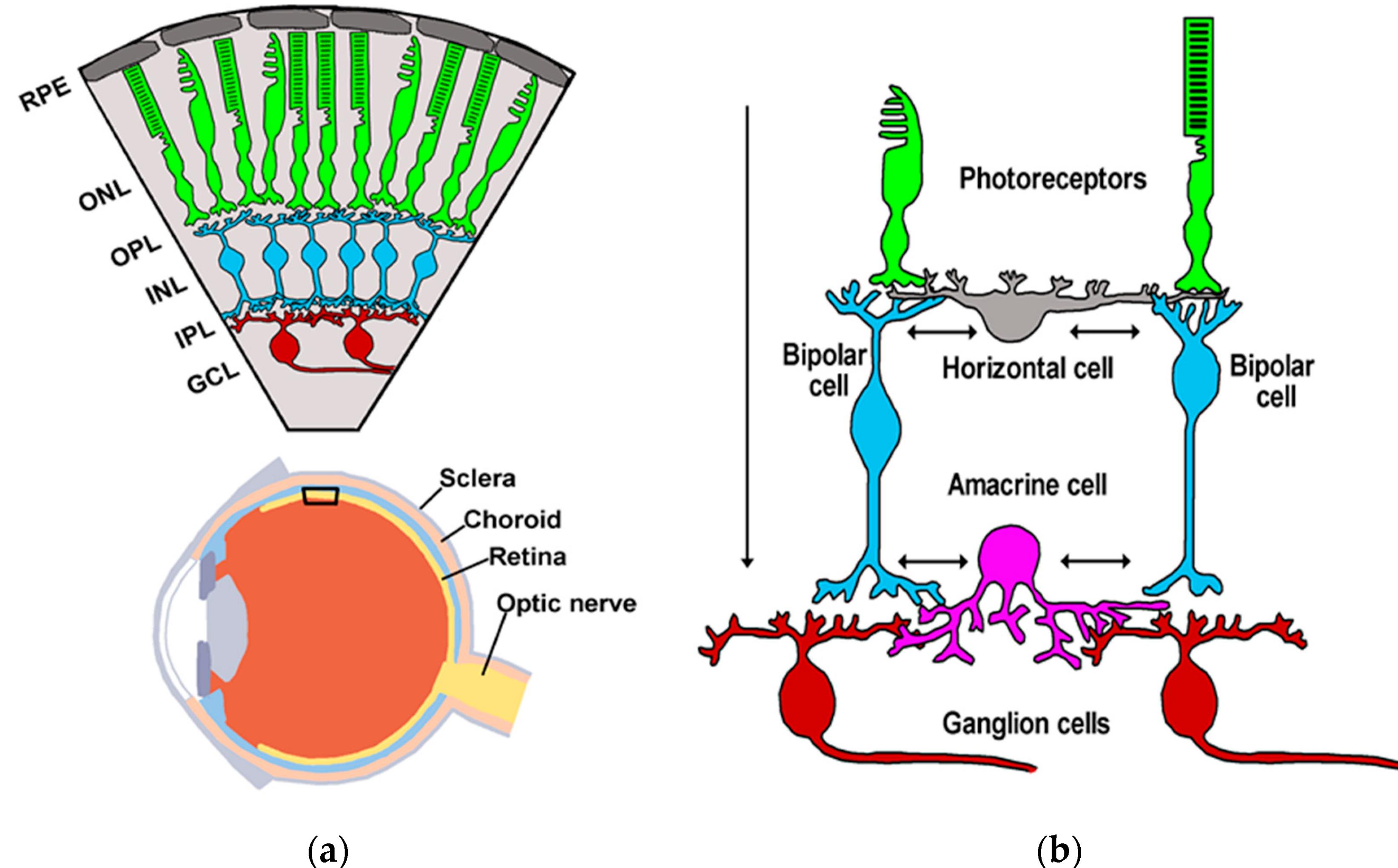
A Second Attempt



Mode 1

Accessibility

Human Visual Perception



Colorblindness Types

Protanopia

Blindness to Red

$\approx 1\%$

Deuteranopia

Blindness to Green

$\approx 1.5 - 5\%$

Tritanopia

Blindness to Blue

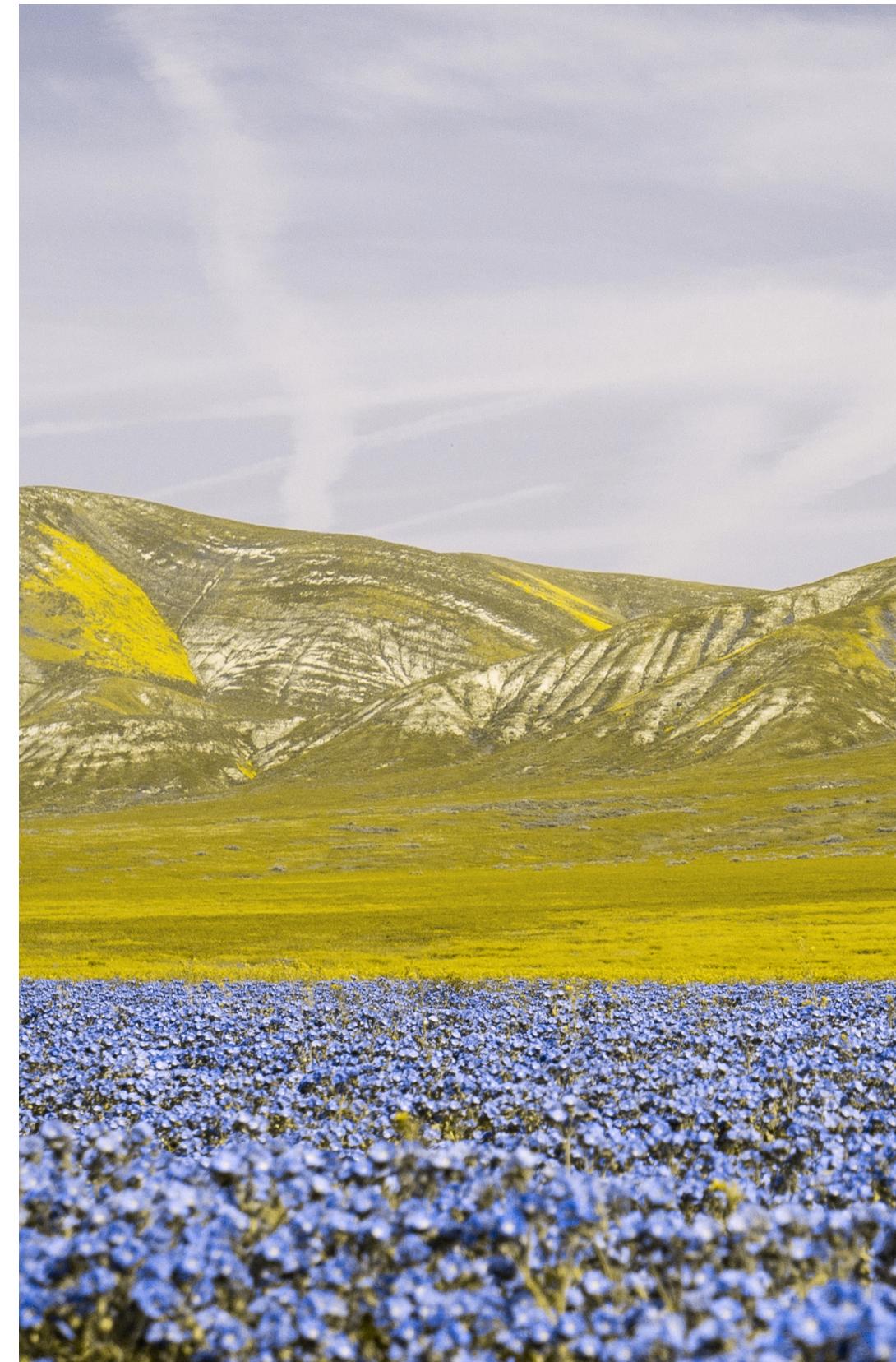
$< 0.01\%$

Colorblindness Types



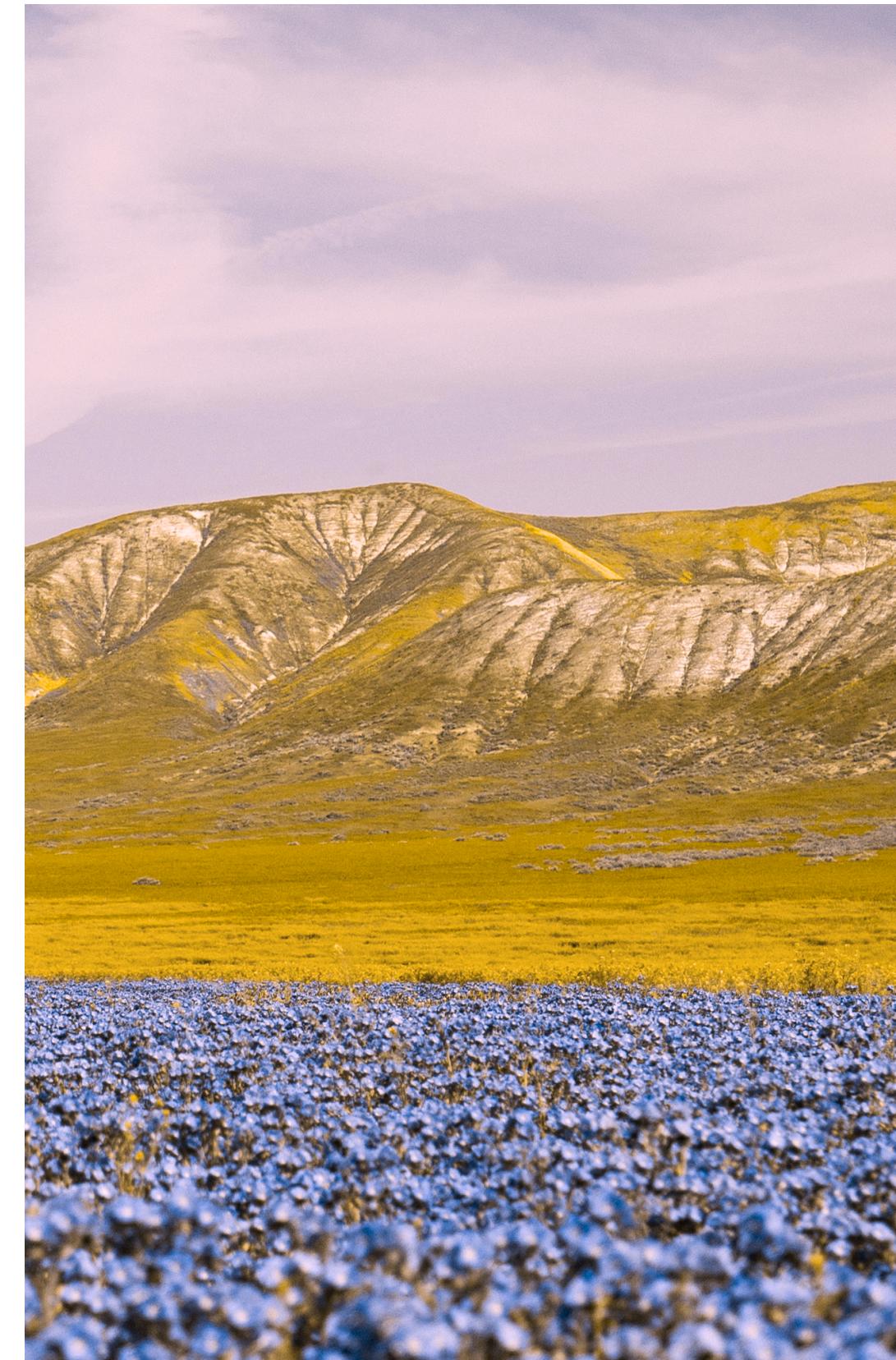
Trichromasy

Normal Vision



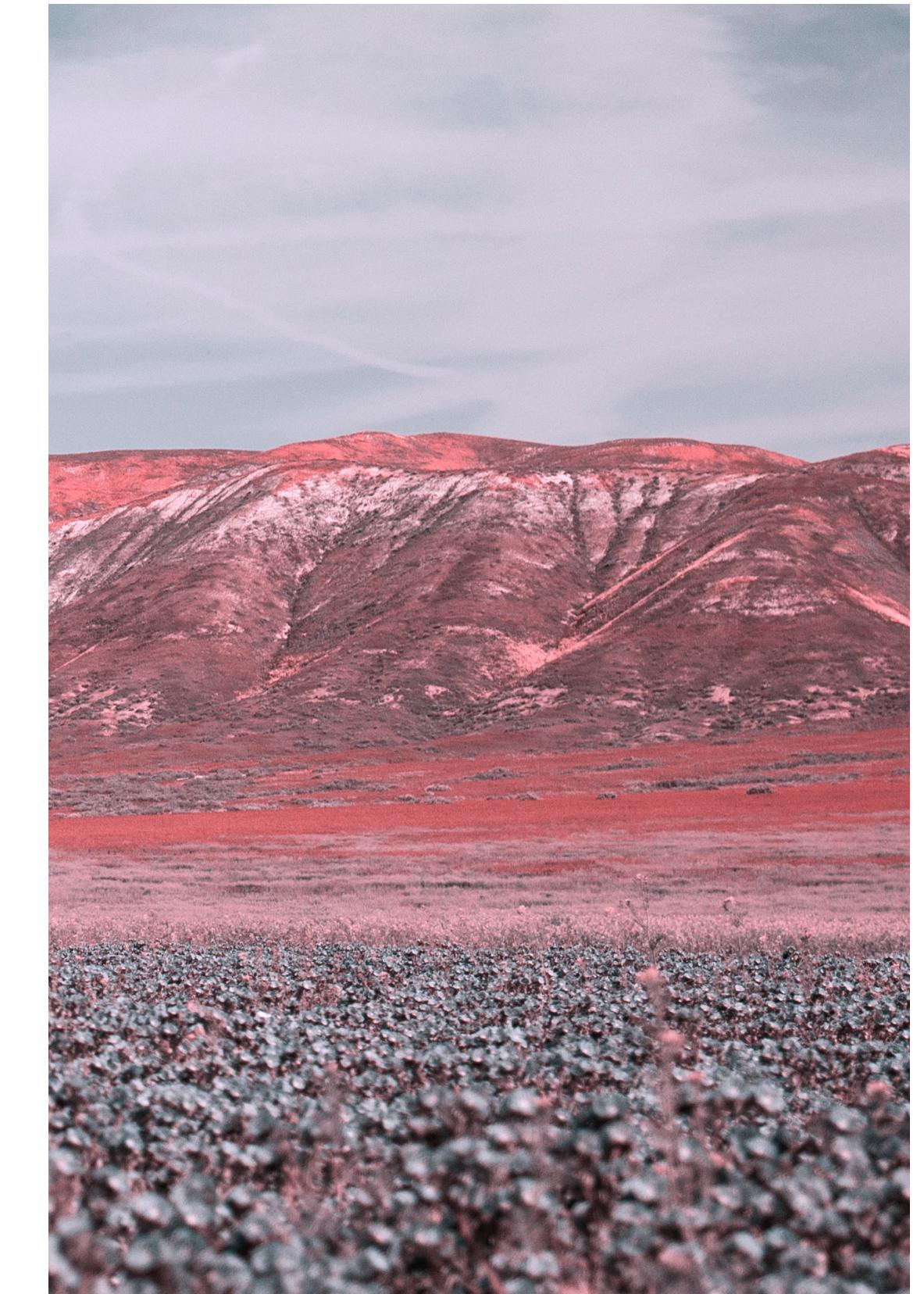
Protanopia

Blindness to Red



Deuteranopia

Blindness to Green



Tritanopia

Blindness to Blue

The Perfect Color Palette

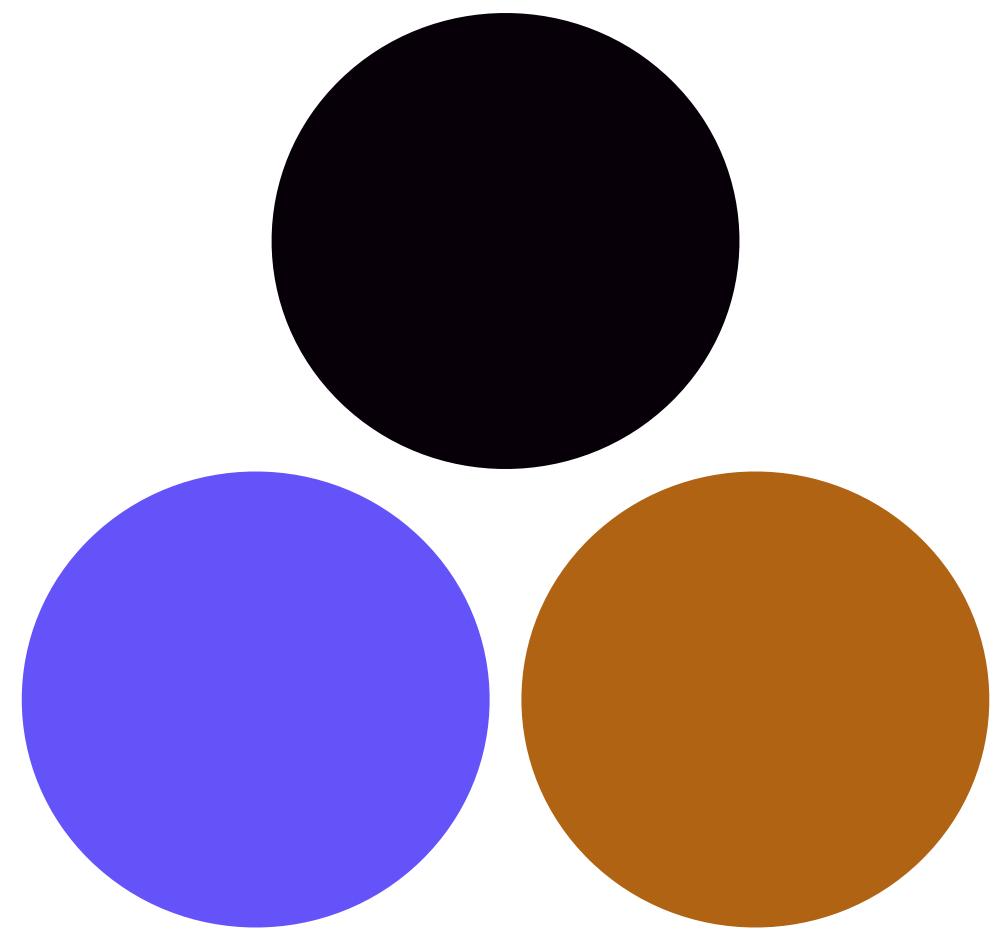
A Third Attempt

$$\underset{c_1, \dots, c_n}{\text{maximize}} \quad \sum_{a \in \{\text{norm., pro., deu., tri.}\}} \lambda^a \left(\sum_{i=1}^{n-1} \left(\sum_{j=i+1}^n (\Delta E(c_i^a, c_j^a)) \right) + \sum_{i=1}^n (\Delta E(c_0^a, c_i^a)) \right)$$

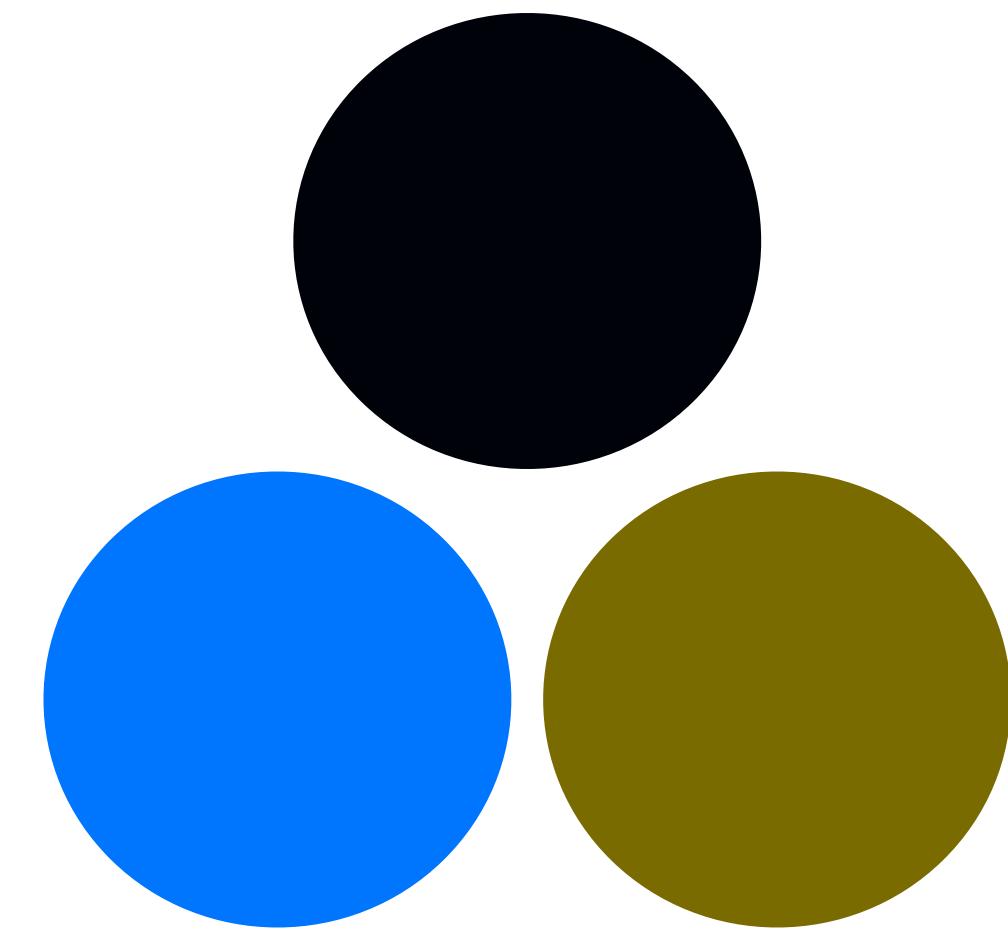
The diagram illustrates the components of the optimization equation. At the bottom, four labels represent different color vision types: 'Normal', 'Protanopia', 'Deuteranopia', and 'Tritanopia'. Arrows point from each of these labels upwards towards the summation term in the equation. The first arrow points from 'Normal' to the first term of the summation. The second arrow points from 'Protanopia' to the second term of the summation. The third arrow points from 'Deuteranopia' to the third term of the summation. The fourth arrow points from 'Tritanopia' to the fourth term of the summation.

The Perfect Color Palette

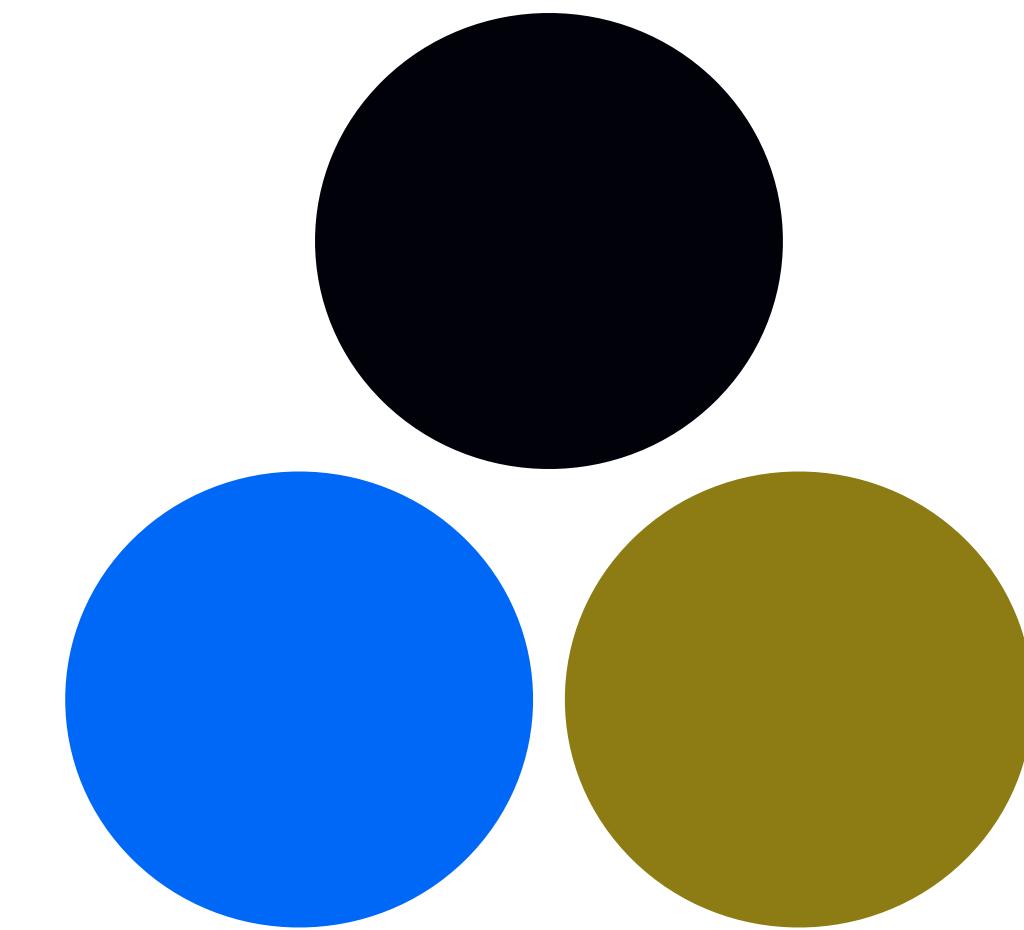
A Third Attempt



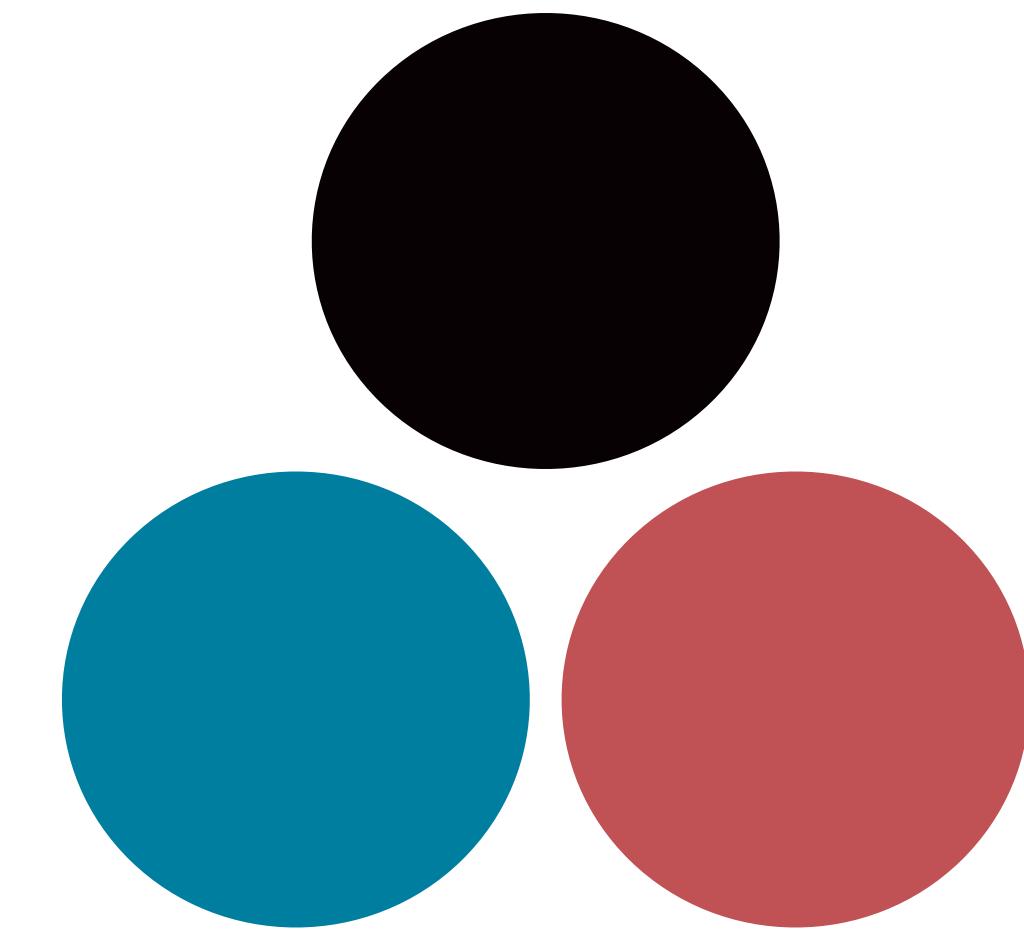
Normal Vision



Protanopia



Deuteranopia



Tritanopia

Let's be honest, this color palette doesn't look that nice

Aesthetics

What is aesthetic?

- Human preferences are highly subjective and common mechanisms are poorly understood
- We need a ΔE for aesthetics!
- Sadly, this doesn't exist 😭
- Data-driven approach: learn a function (i.e., neural network) that given two input colors predicts how aesthetically pleasing someone finds the combination of colors
- We need your help! Will be sending out a questionnaire early next week. As incentive: stylish color palettes for presentations and publications!

Summary

- Building **distinguishable** and **accessible** color palettes is just an optimization problem
- It works with an **arbitrary number** of colors and you can use **seed colors**
- **LAB** colorspace and **ΔE** are useful to calculate how distinguishable colors are
- The three most common types of colorblindness are **protanopia**, **deutanopia**, and **tritanopia**
- Defining what is aesthetic is hard! **Survey!**

Thank You