

Lecture 7: Color Vision

Yuhao Zhu

<http://yuhaozhu.com>
yzhu@rochester.edu

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Computer Imaging & Graphics

The Roadmap

Theoretical Preliminaries

Human Visual Systems

Color in Nature, Arts, & Tech

(a.k.a., the birth, life, and death of light)

Digital Camera Imaging

Modeling and Rendering

Applications



Introduction and Overview

Photoreceptors

Color Vision and Colorimetry

Color Production

Light and Dark Adaptation

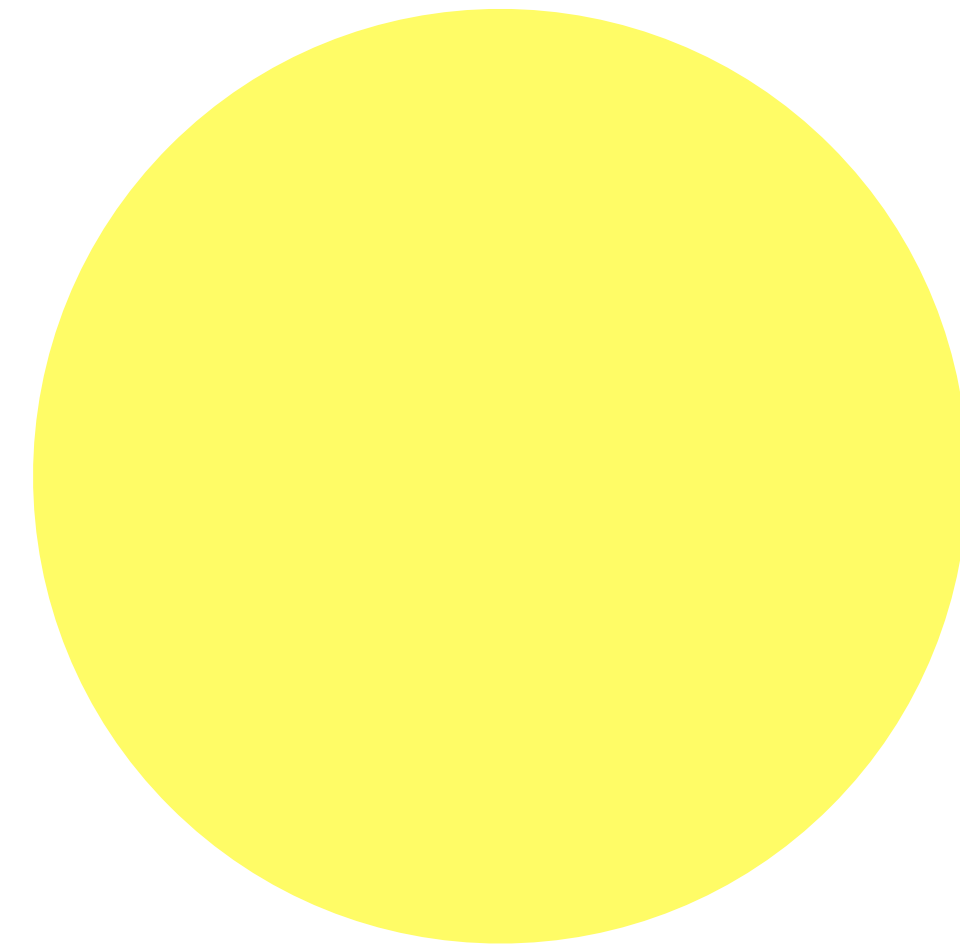
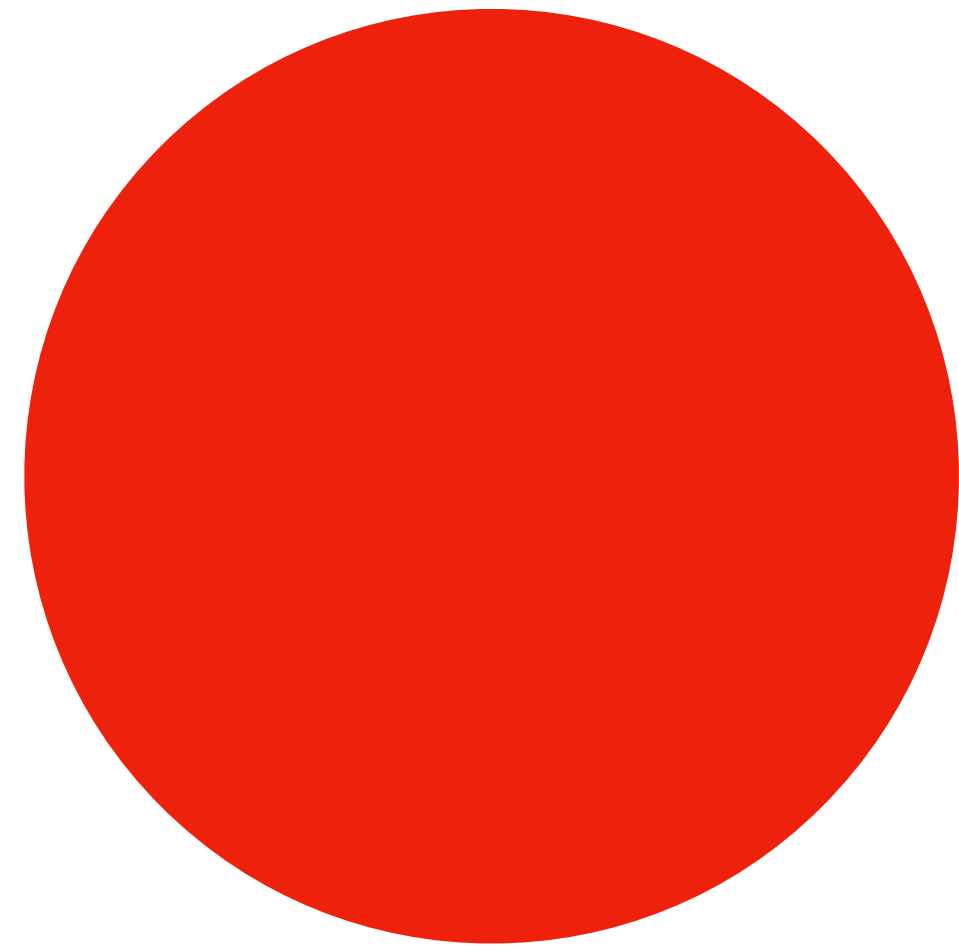
Retinal Representations

Red Without Any Red Pixel

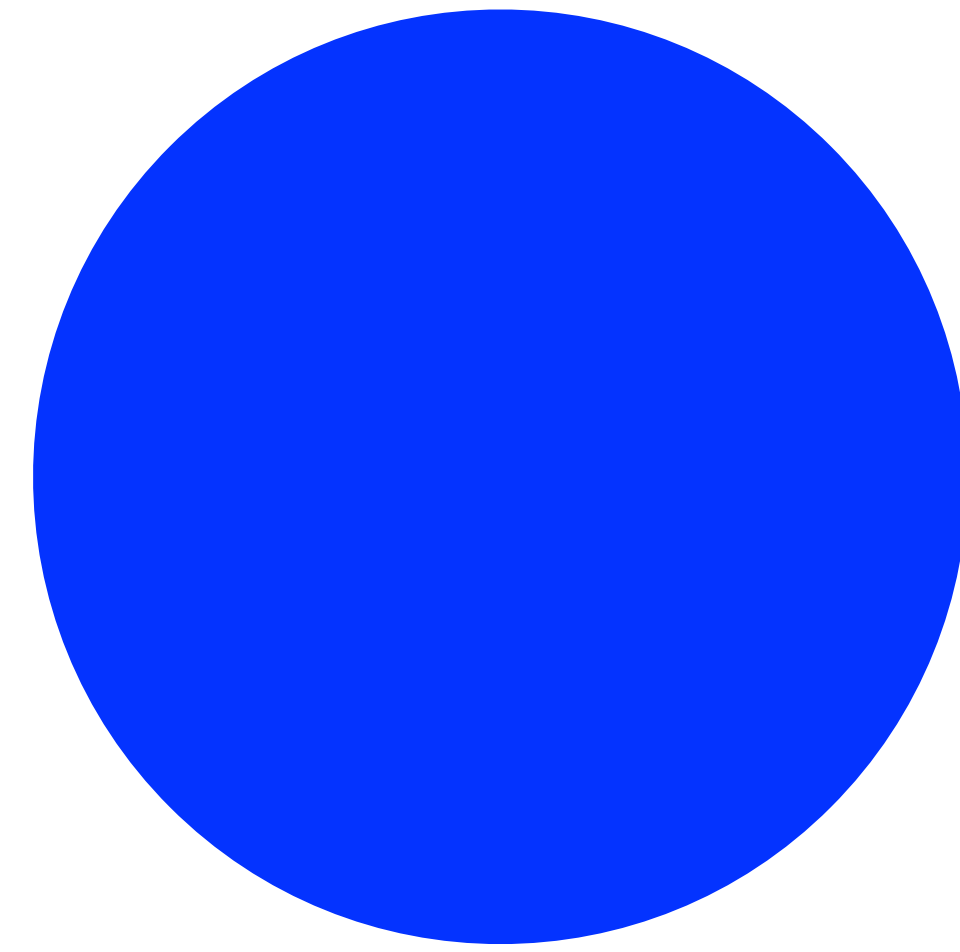
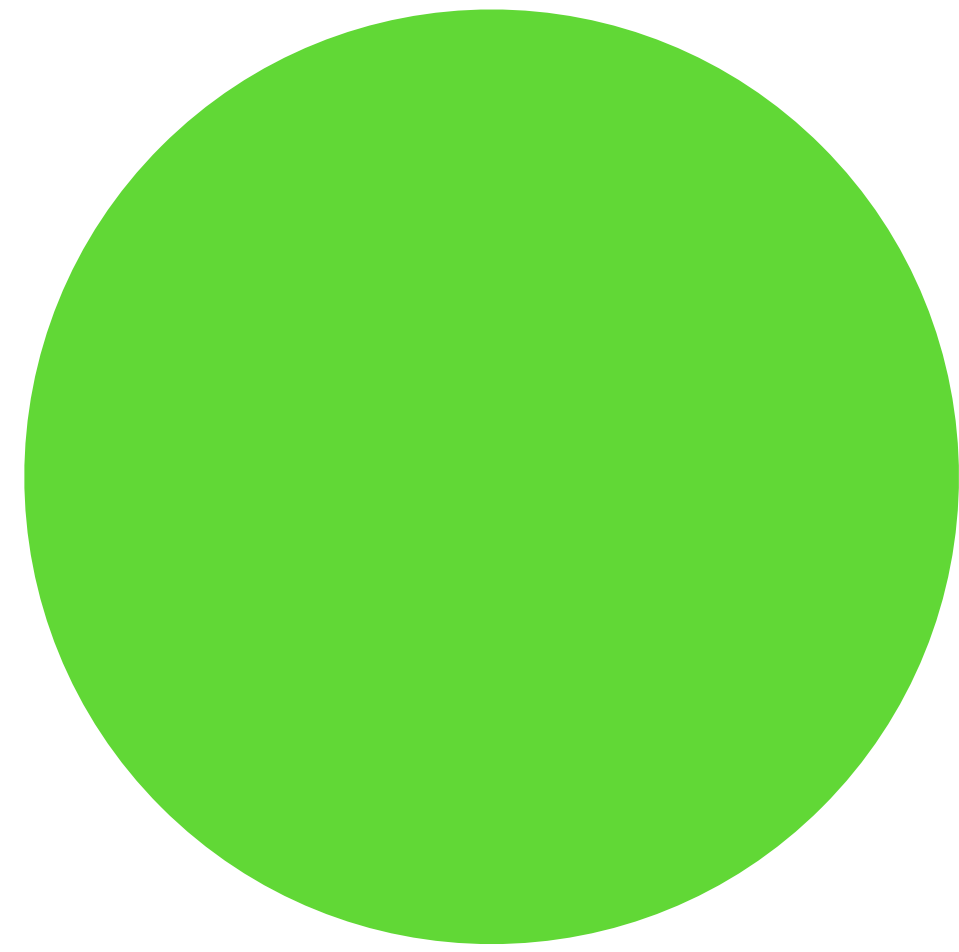


The Dress



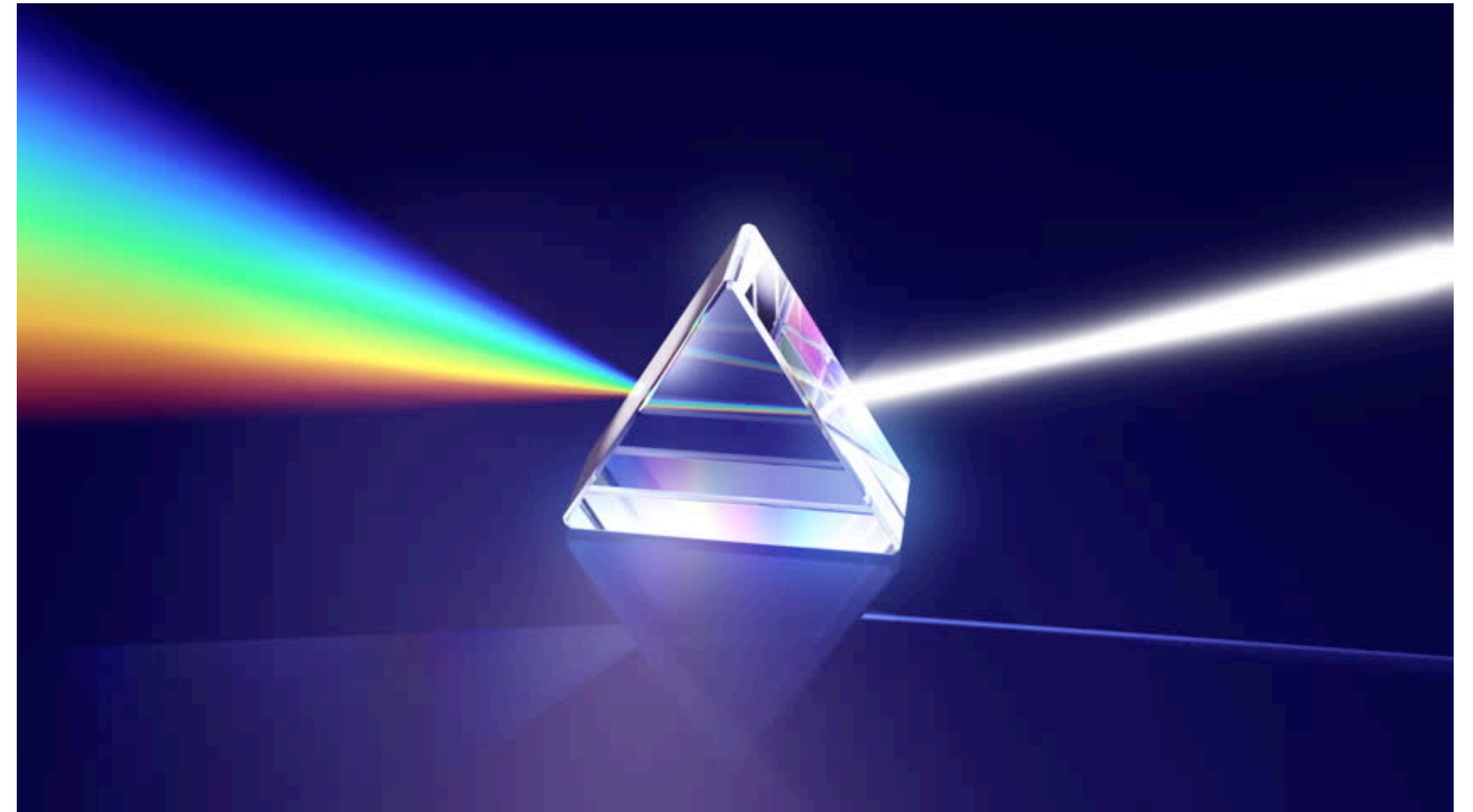


X

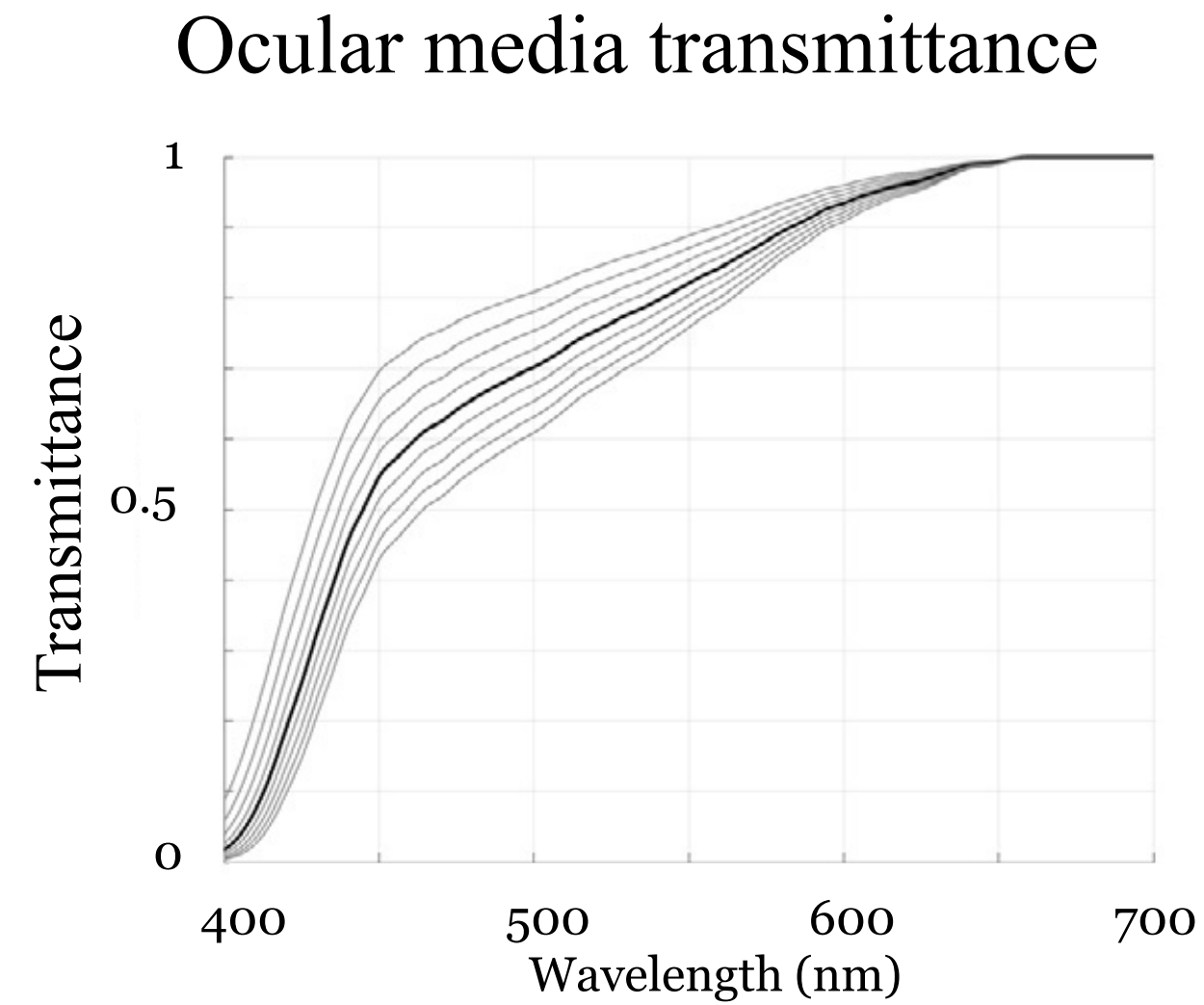


Wavelength Encoding in Photoreceptors

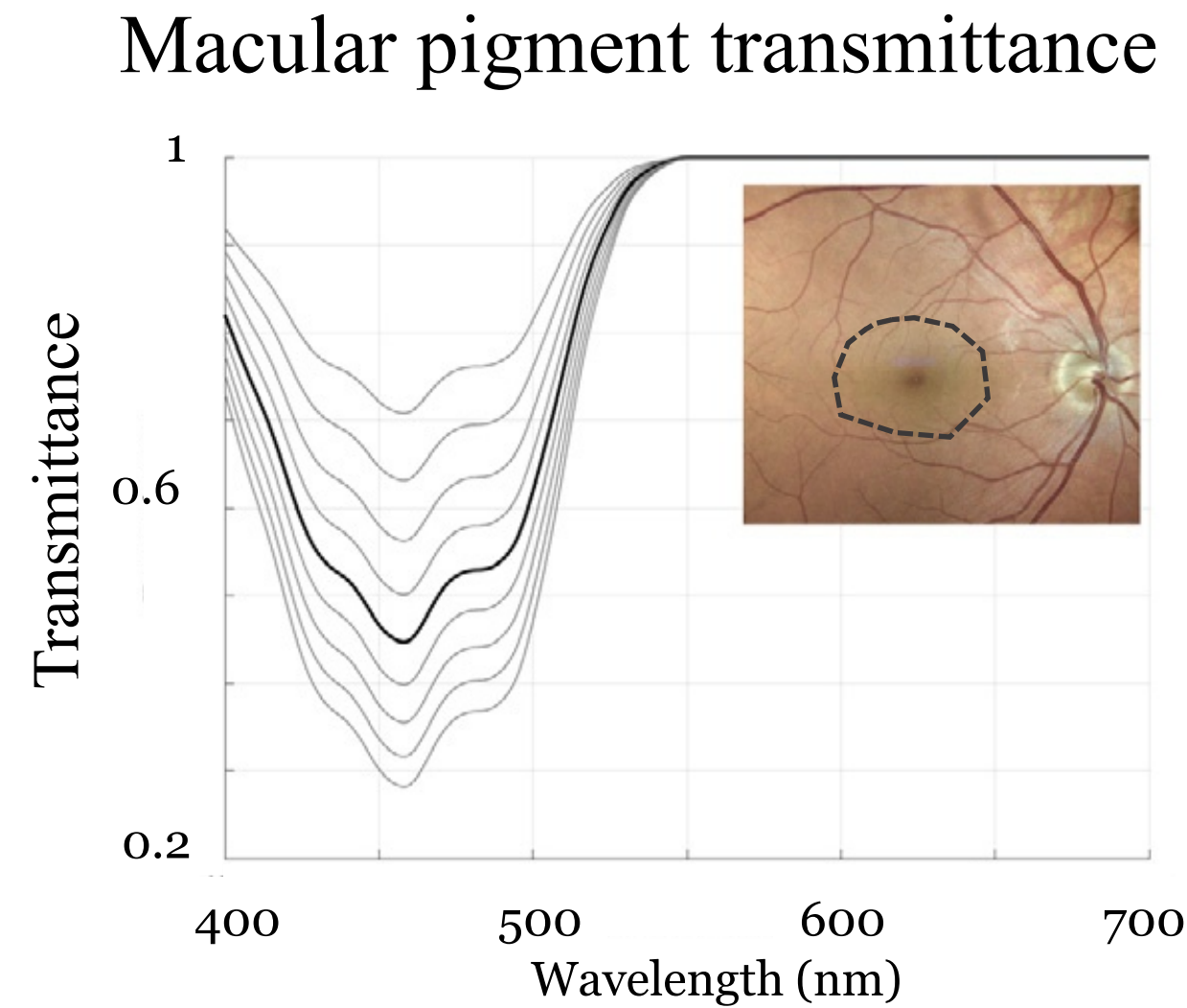
Light Spectrum



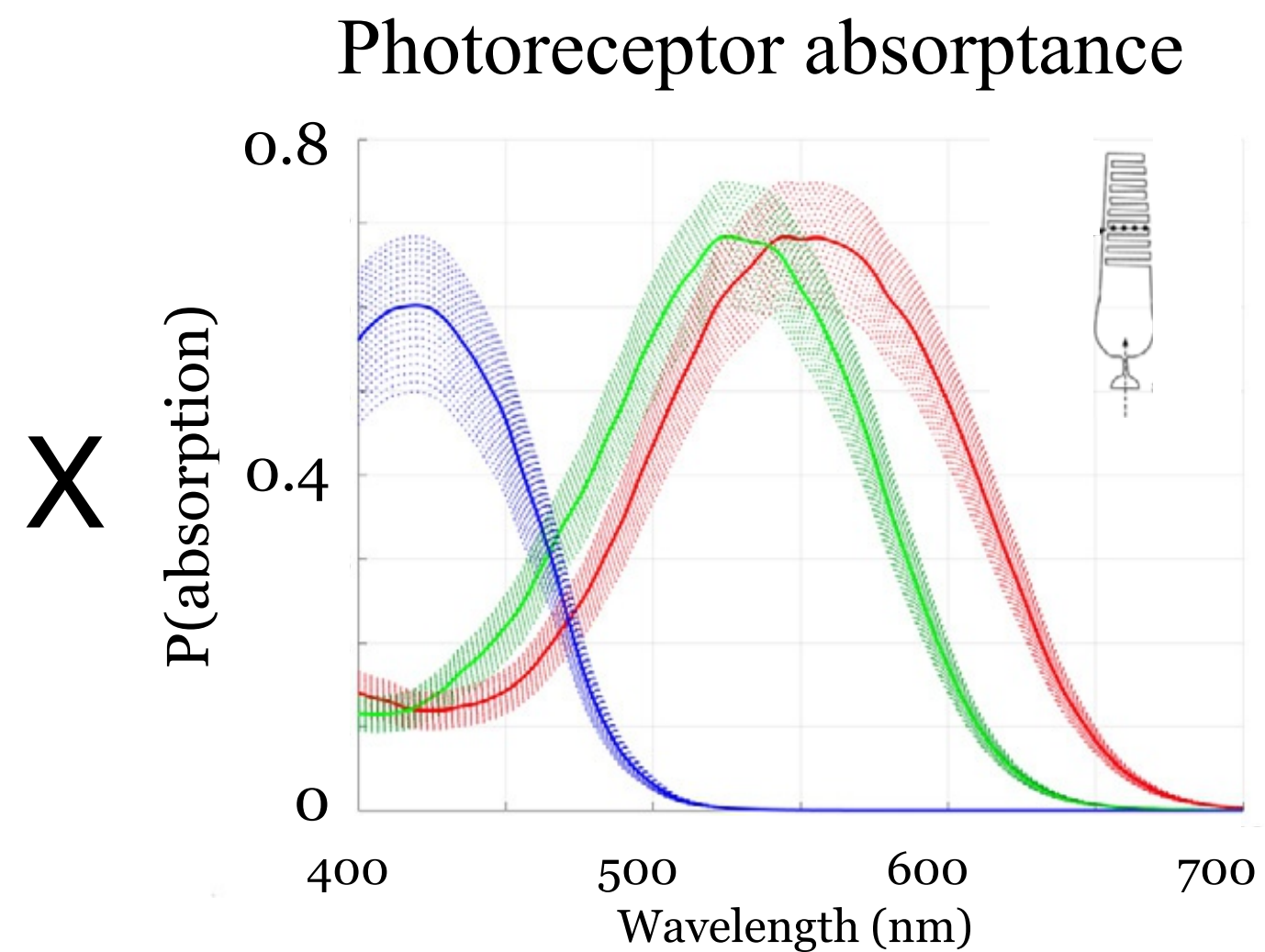
Cone Fundamentals (Cornea-Referred Spectral Sensitivity)



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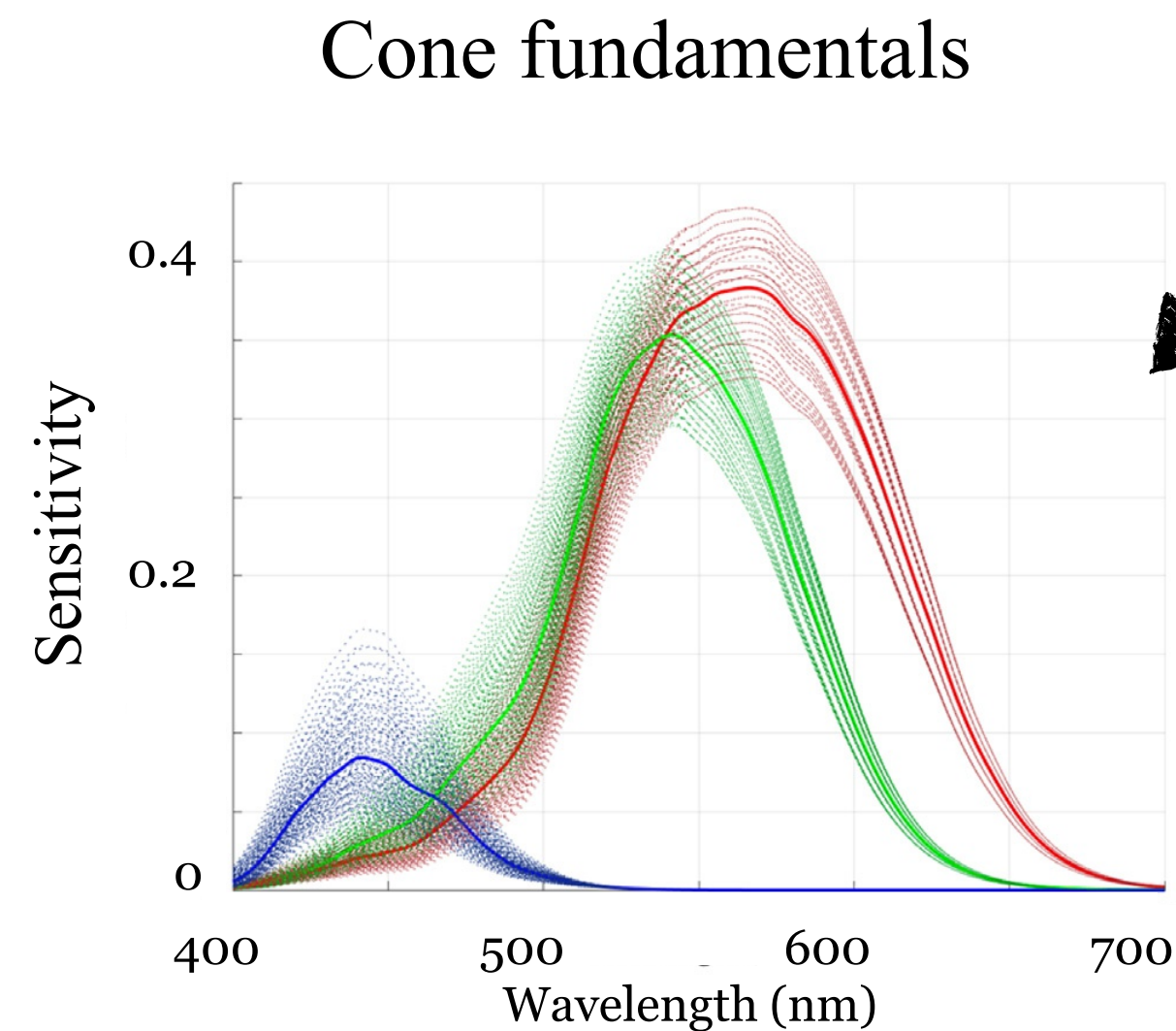


Percentage of photons arriving at the cornea that is absorbed by the photoreceptors (at each wavelength)



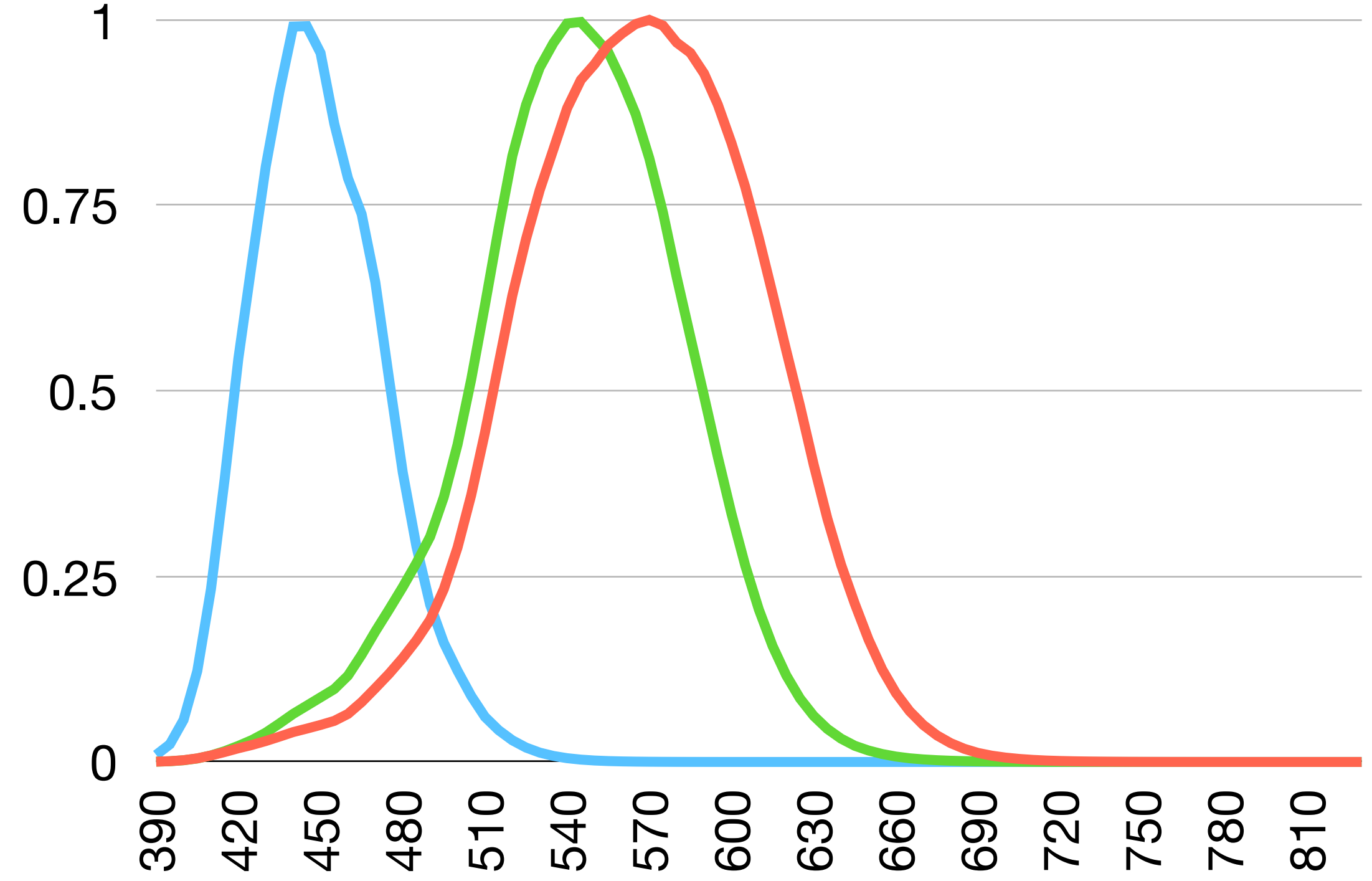
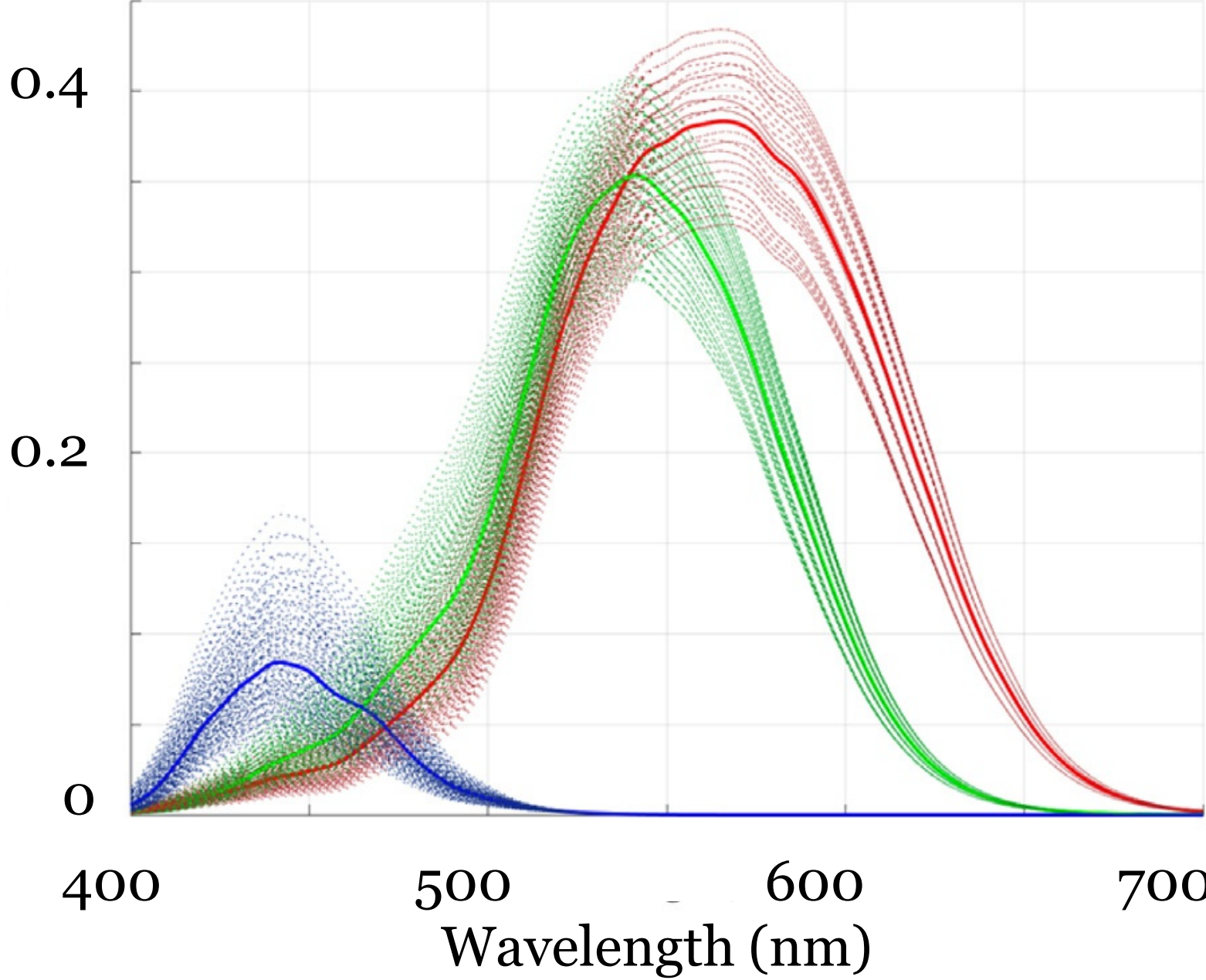
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Equal-Energy Cone Fundamentals

Relative percentage of photons absorbed assuming lights at each wavelength have the same power/energy

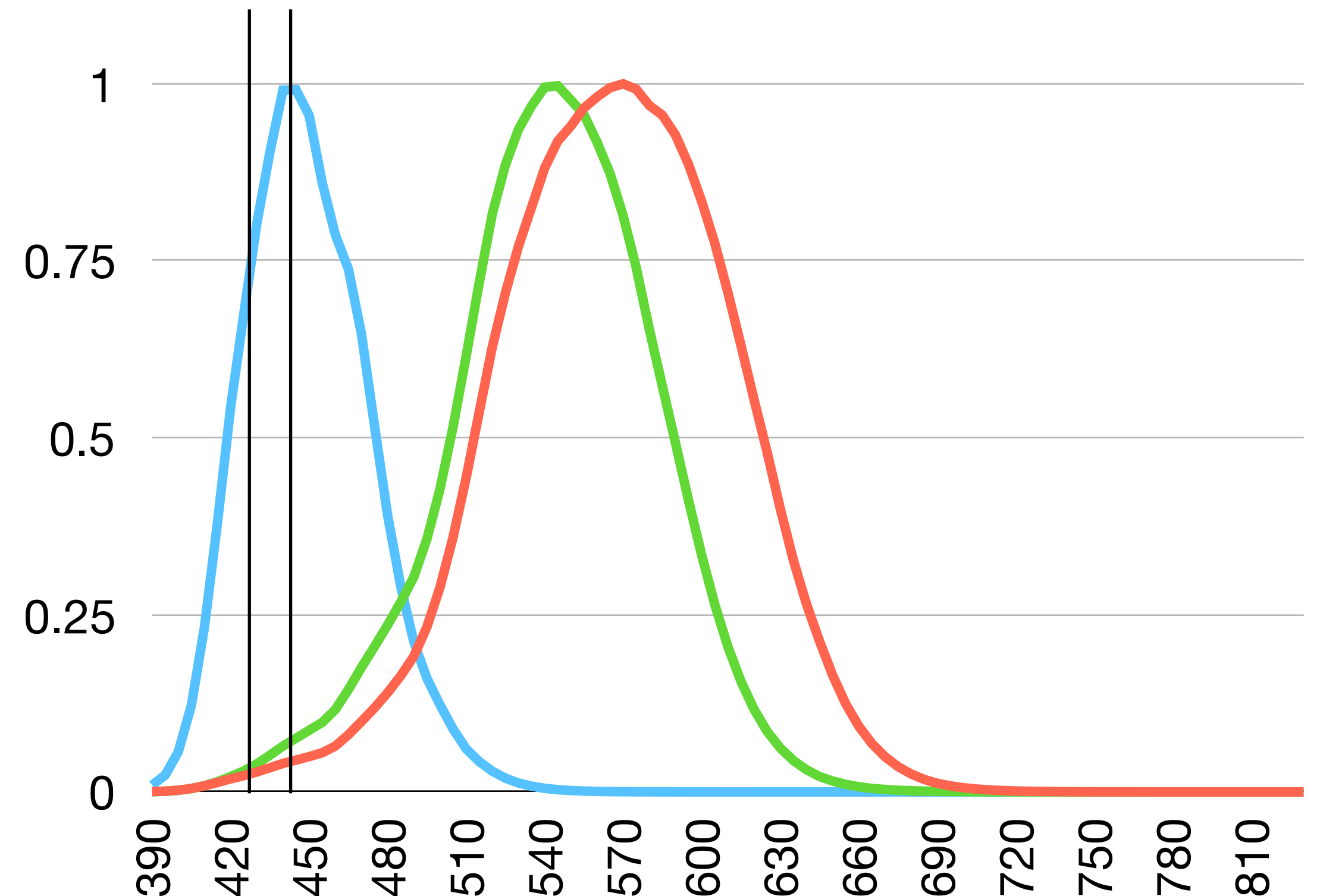


Normalized each curve to peak at unity, and change equal-quantal to equal-energy

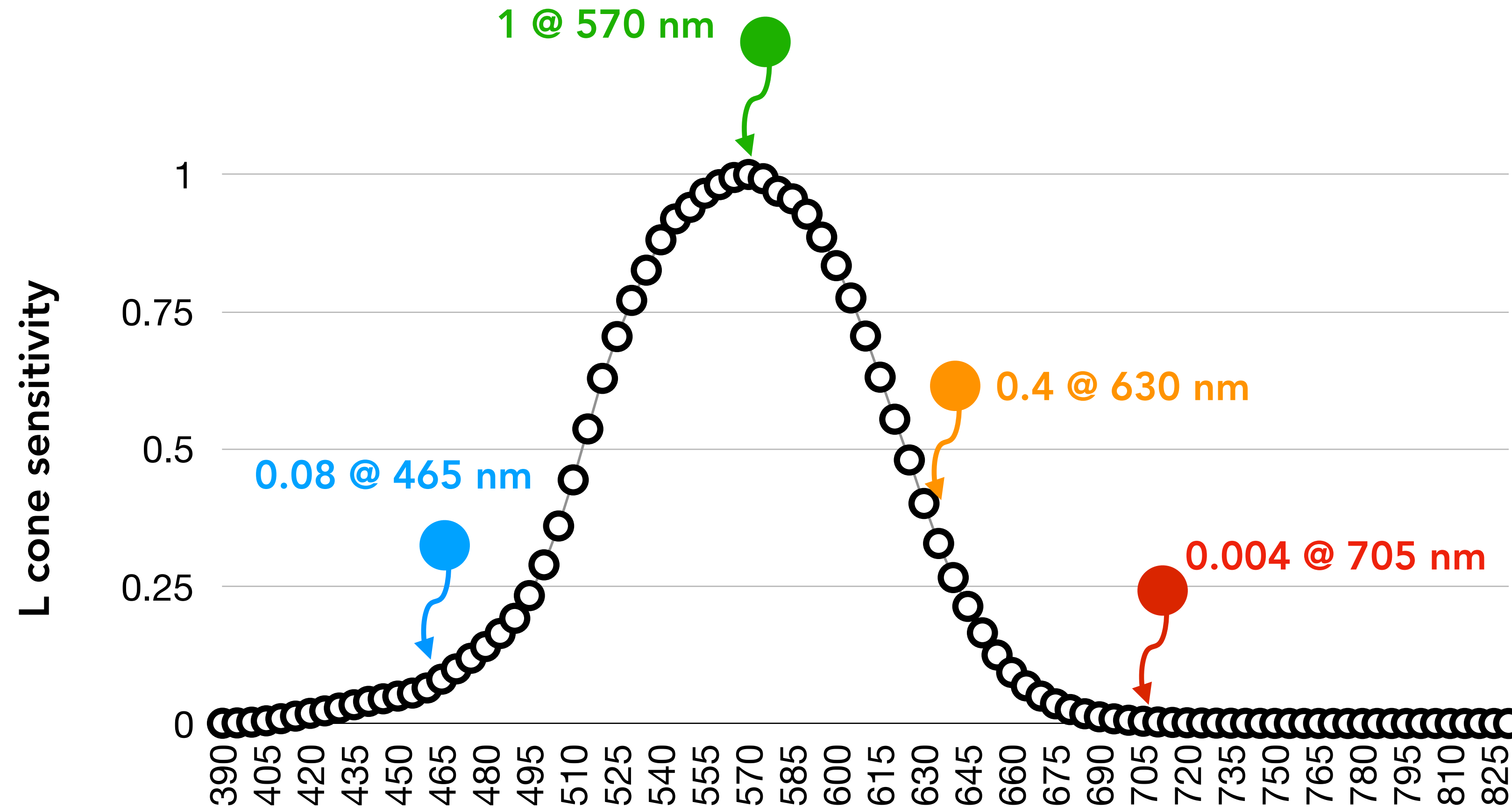
Equal-Energy Cone Fundamentals

- For S cone, the relative sensitivity at 445nm is 1 and the relative sensitivity at 428 nm is 0.75. This means:
 - Given two lights, one at 445 nm and the other at 428 nm, that have the same power, the relative photon absorption at 428 nm is 75% of that at 445 nm.

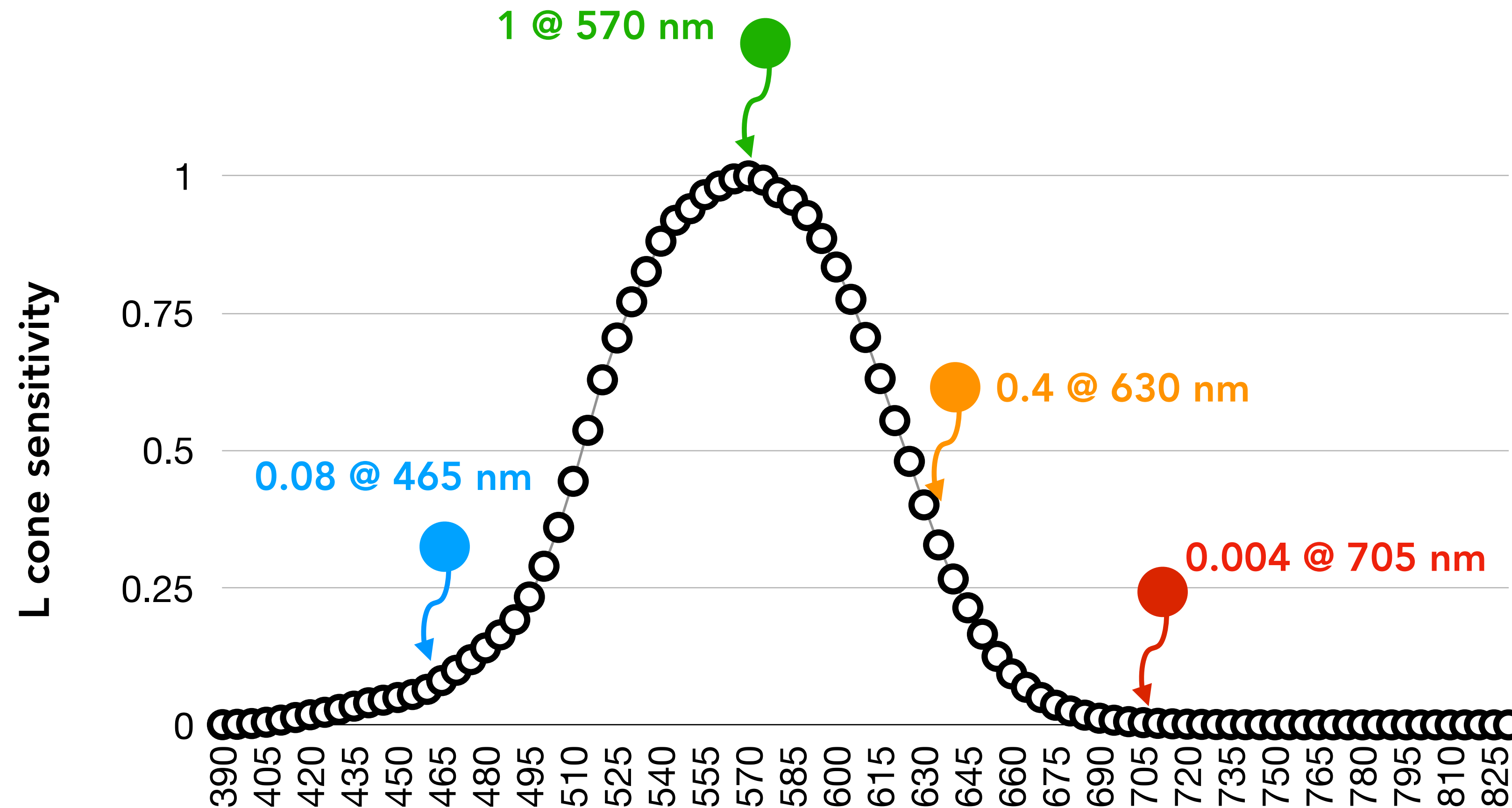
Relative percentage of photons absorbed assuming lights at each wavelength have the same power/energy



Spectral Sensitivity of L Cones



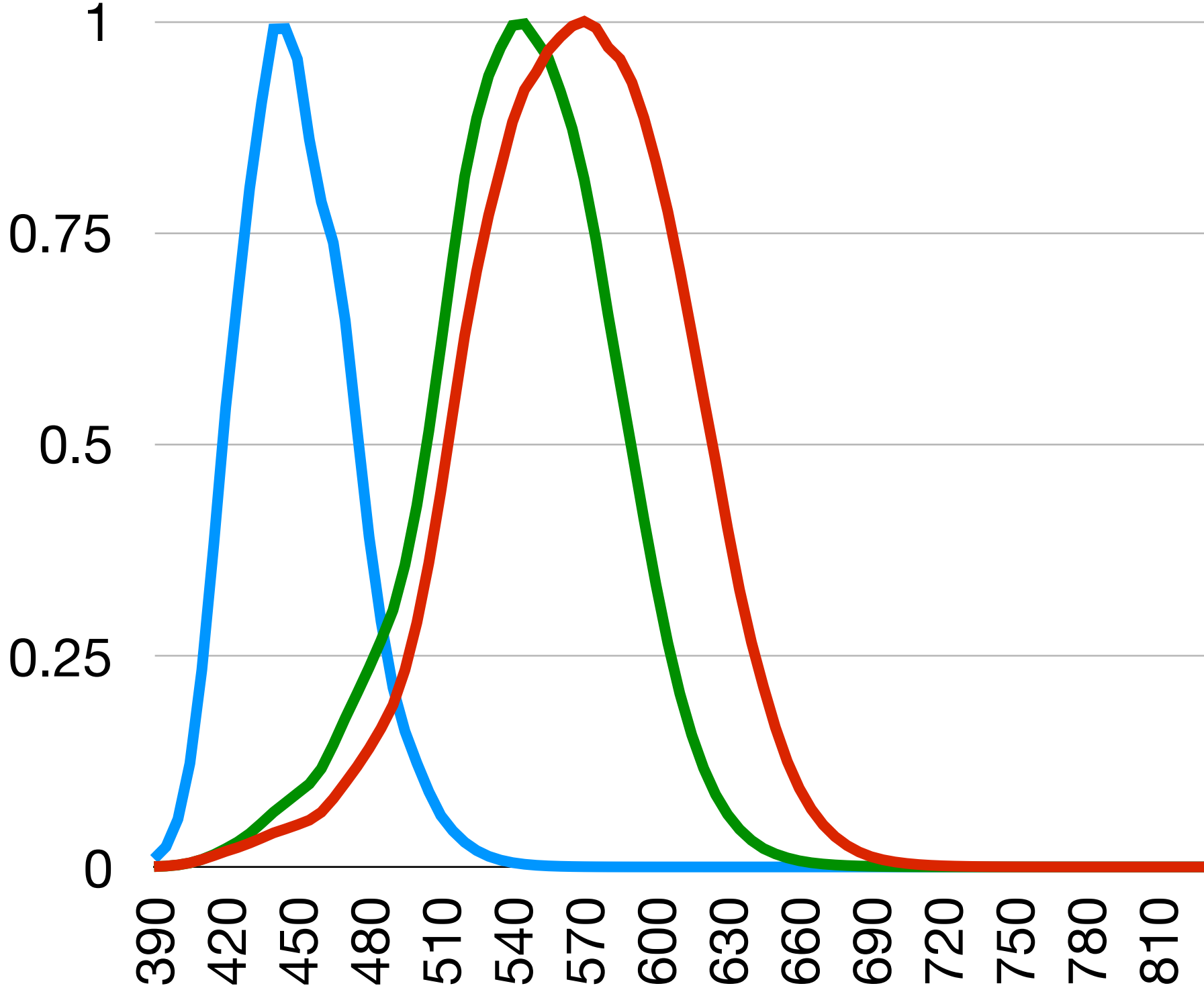
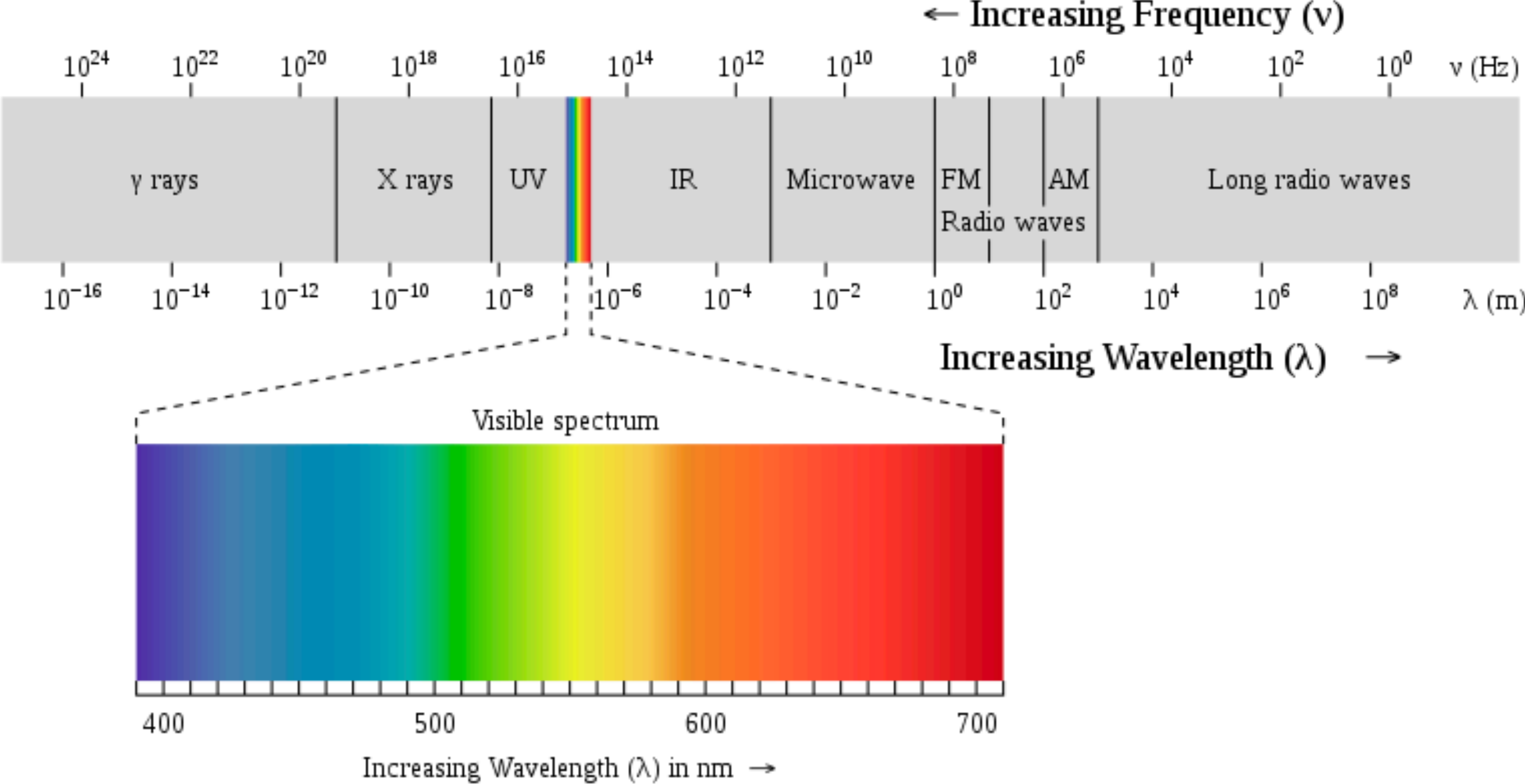
If We Had Only L Cones



- These lights will be perceived as the same light:
 - 570 nm at 1 W
 - 465 nm at 12.5 W
 - 630 nm at 2.5 W
 - 705 nm at 250 W
- Because the brain will receive exactly the same signal

Interlude: Invisible Light

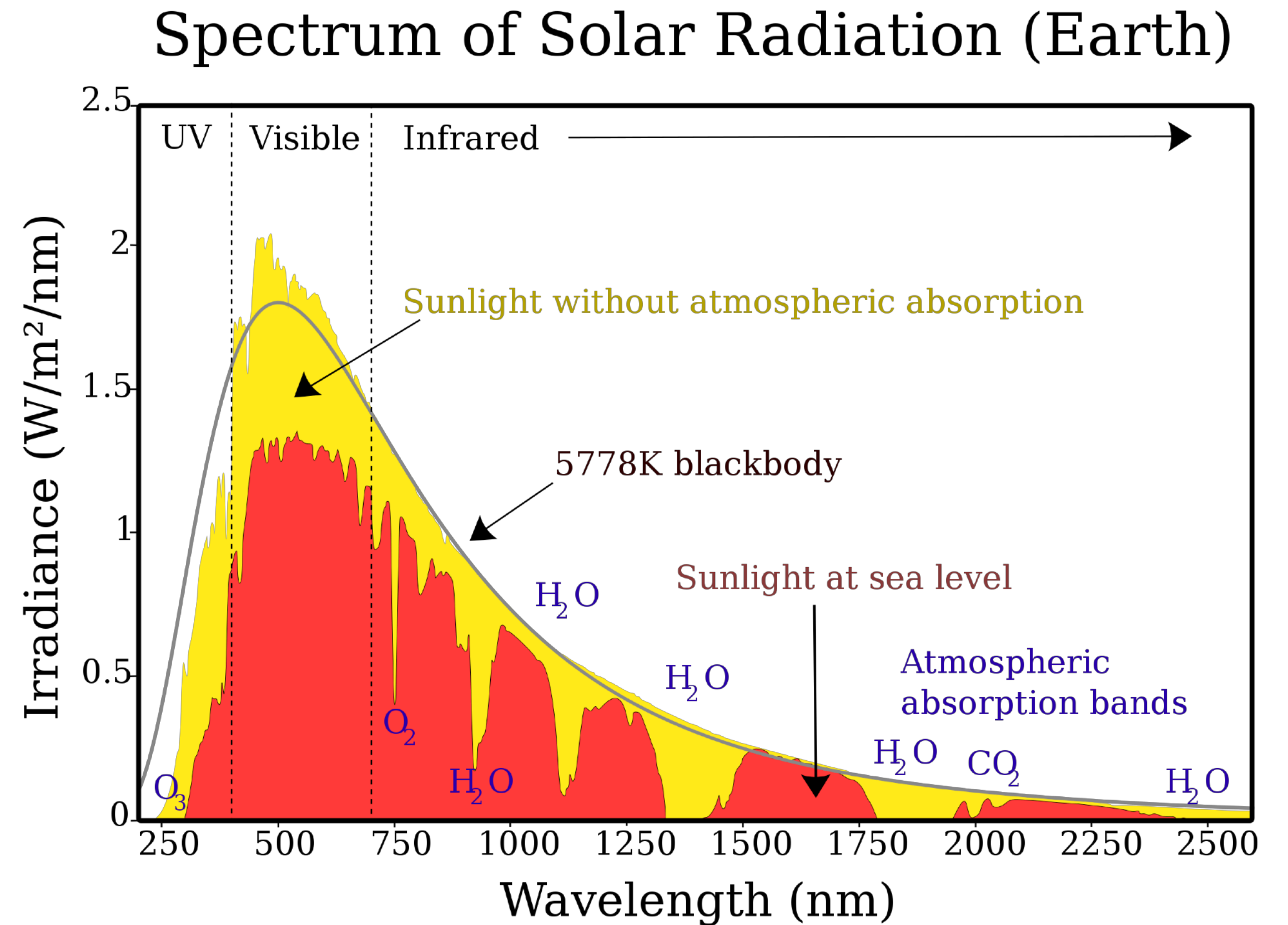
- “Invisible”: Lights (electromagnetic waves) not interacting with cones cells.



Stockman & Sharpe (2000)

Interlude: Invisible Light

- Sunlight has invisible components, which don't interact with retina photoreceptors, but interact with other kinds of cells.
- Case in point: skin cancer, where Ultra-Violet (UV) lights interact with skin cells.
- Another example: Infra-Red (IR) cameras can "see" things we can't.
- They use materials that do interact with IR lights. More later.



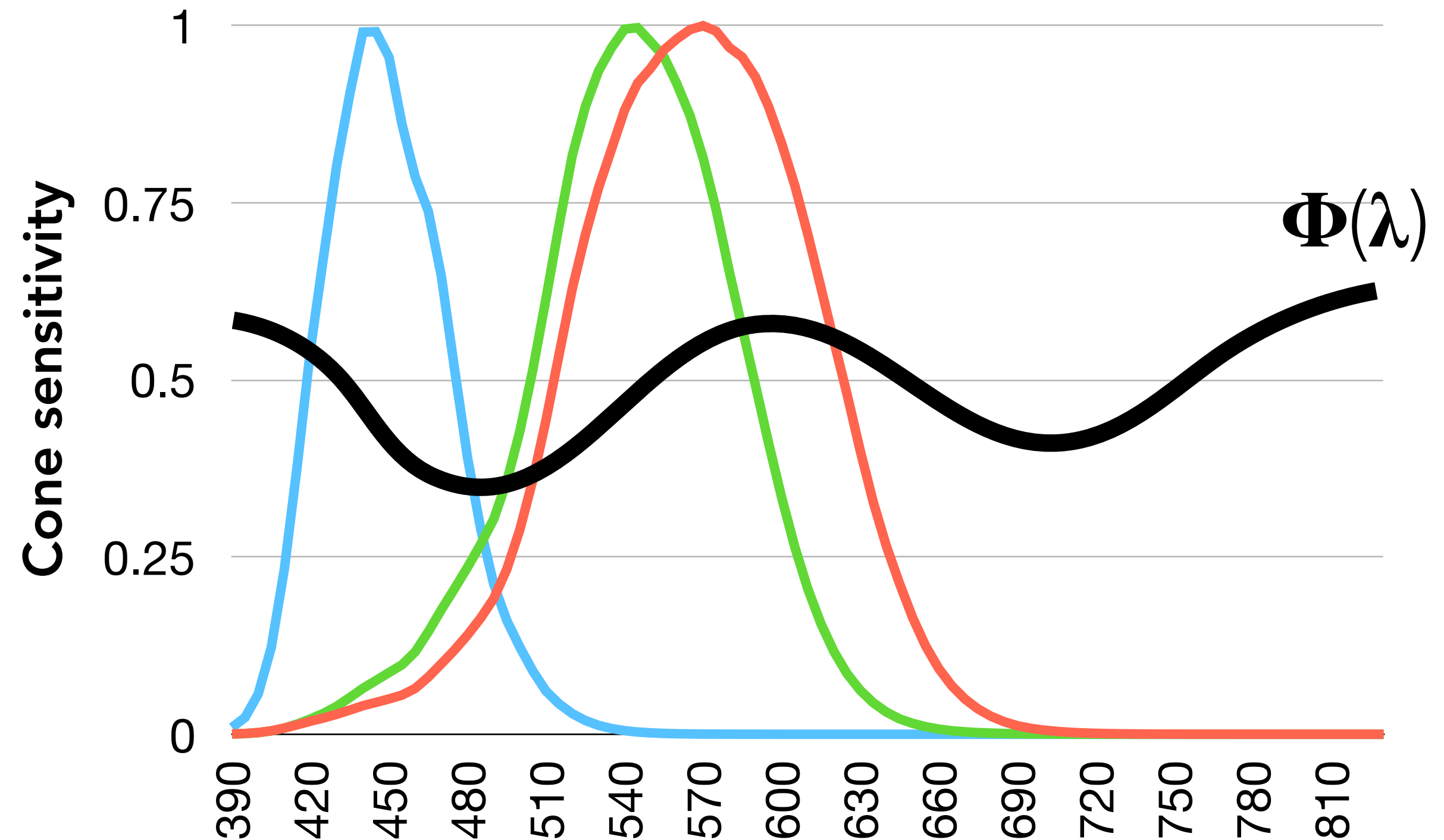
Total Cone Response

- Given a light $\Phi(\lambda)$, we can calculate the total responses of the L, M, and S cone cells. The three signals are called the **tristimulus values** of the light.

$$L = \sum_{\lambda=380}^{780} \Phi(\lambda)L(\lambda)$$

In practice both the SPD and the cone responses are given at discrete intervals.

$$L = \int_{\lambda} \Phi(\lambda)L(\lambda)d\lambda$$



Stockman and Sharpe (2000)

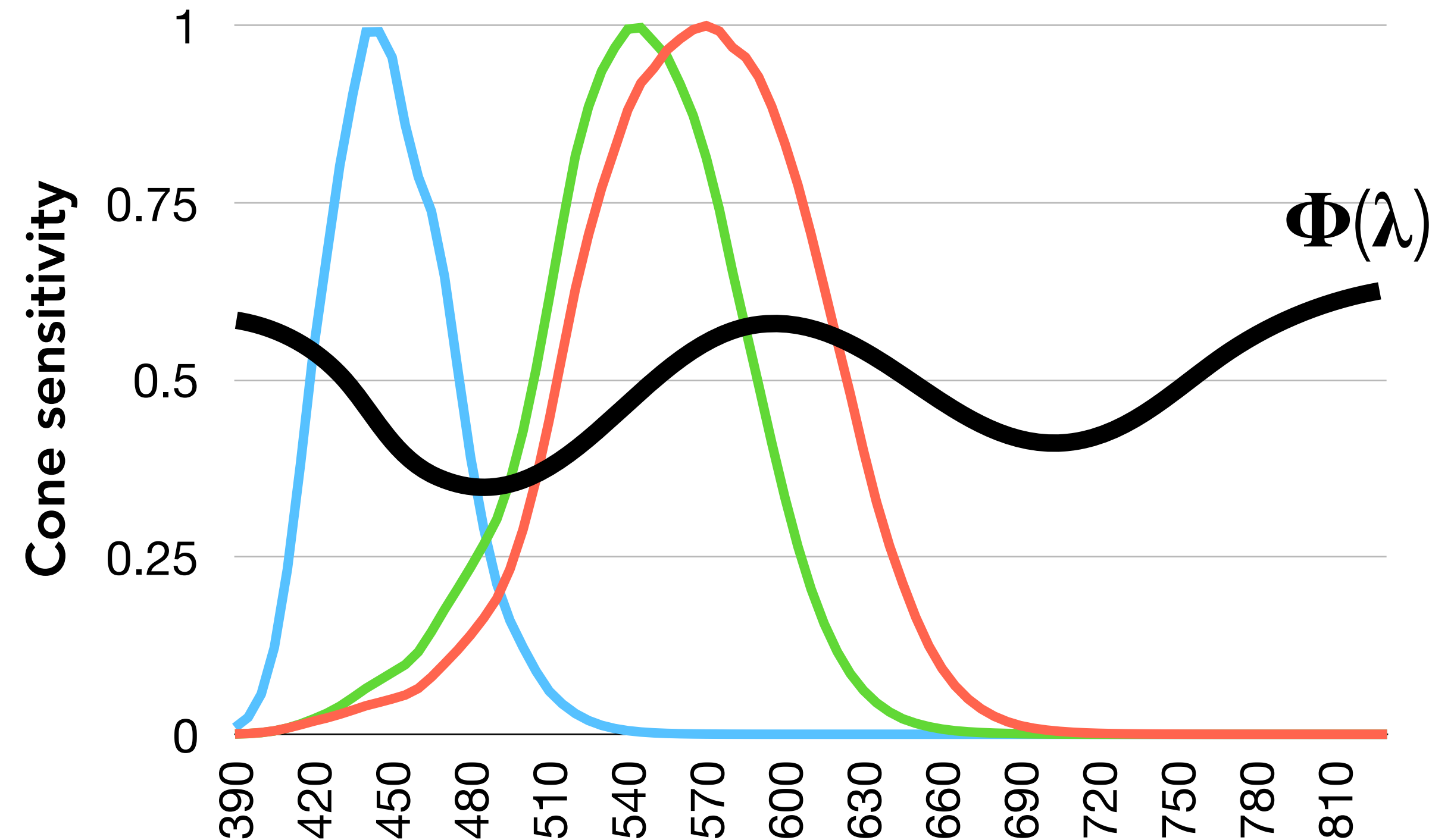
Total Cone Response

- Any light could be expressed as a $\langle L, M, S \rangle$ triplet.

$$L = \sum_{\lambda=380}^{780} \Phi(\lambda)L(\lambda)$$

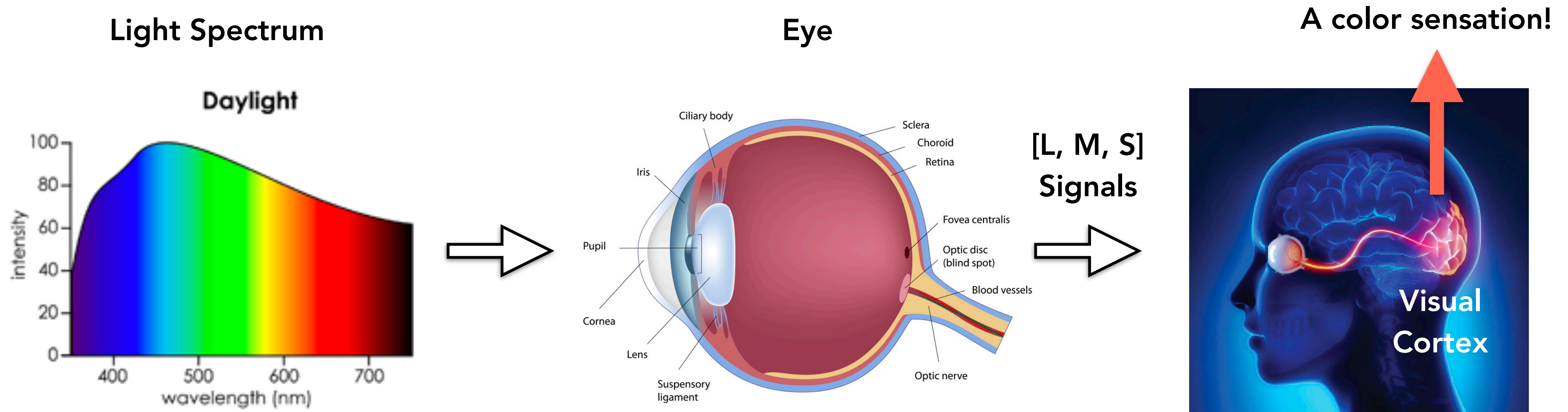
$$M = \sum_{\lambda=380}^{780} \Phi(\lambda)M(\lambda)$$

$$S = \sum_{\lambda=380}^{780} \Phi(\lambda)S(\lambda)$$



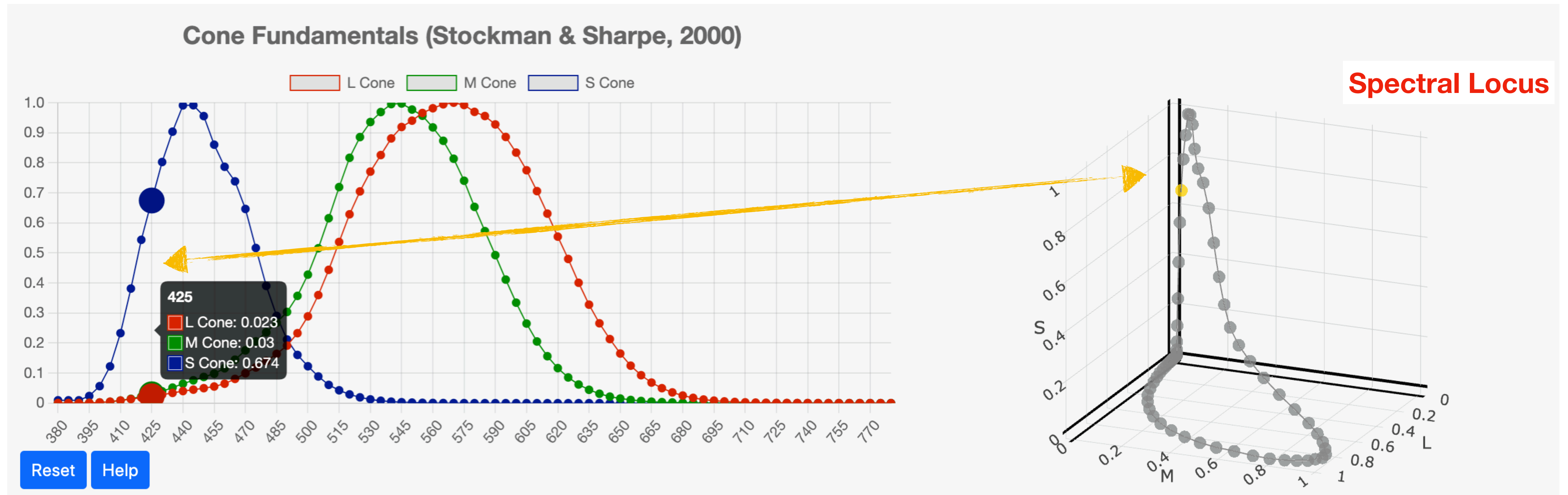
Stockman and Sharpe (2000)

Brain Receives Only the LMS Signals, not Light!



- A particular **LMS** combination leads to a particular color sensation.
- This is a huge dimensionality reduction: the light spectrum is a very high dimensional vector (numerous wavelengths), but is transformed by the retina to only a three-dimensional vector!

Visualizing Spectral Lights in the LMS Color Space



Play with an interactive app here: <https://horizon-lab.org/colorvis/cone2cmf.html>

The LMS Color Space

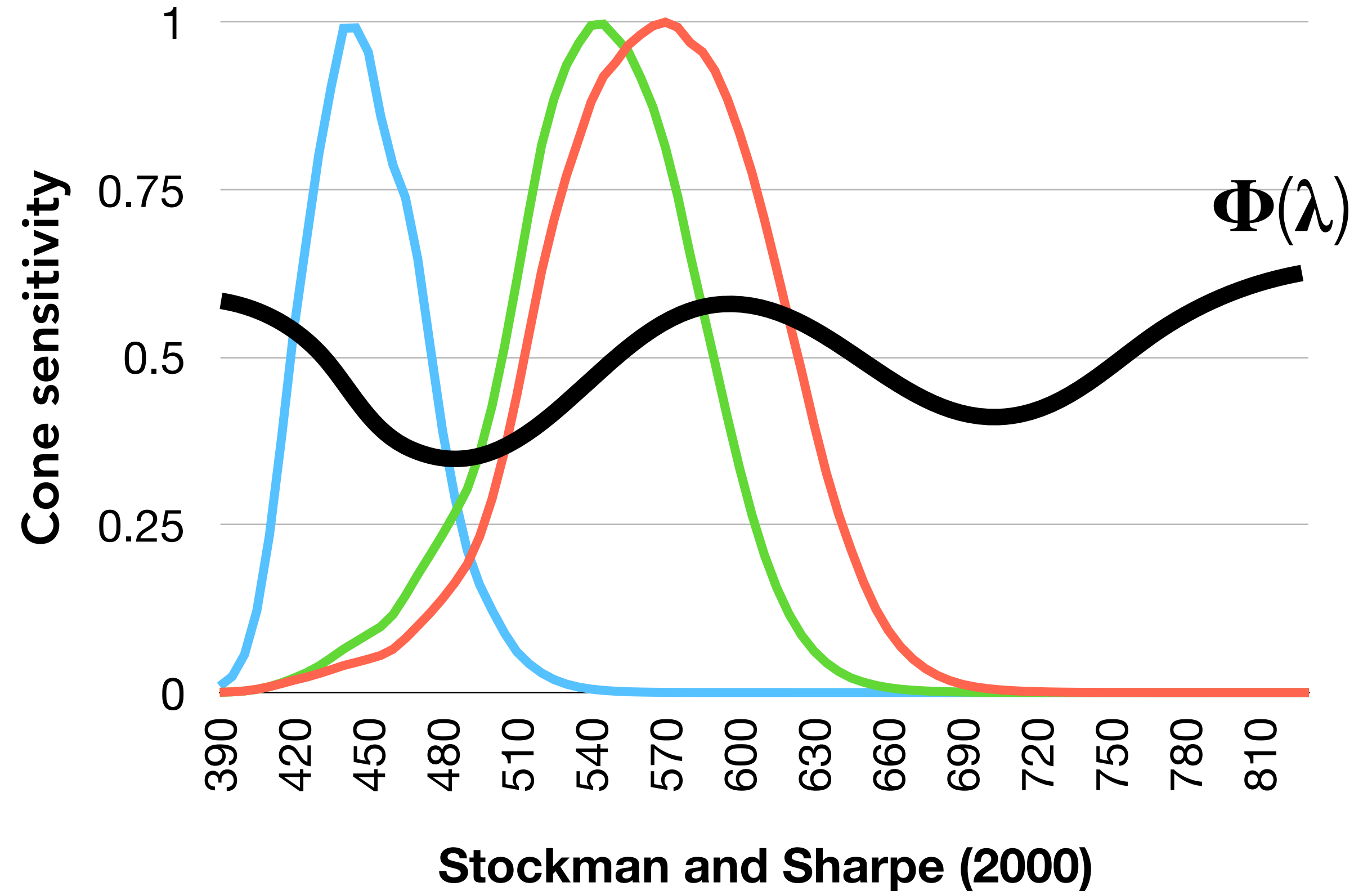
- By expressing any light's color as a $\langle L, M, S \rangle$ point, we have inherently defined a 3D color space, in which every color is a point.
- See visualization here: <https://horizon-lab.org/colorvis/chromaticity.html>.
- What if we uniformly double the power at each wavelength? How would the corresponding $\langle L, M, S \rangle$ change?

Two Fascinating Questions

- 1. Does any arbitrary point in the LMS space correspond to a color?
- 2. Will there be multiple lights that correspond to the same point, i.e., color in the LMS space?

Recall: Calculating Total Cone Responses

$$L = \sum_{\lambda=380}^{780} \Phi(\lambda)L(\lambda)$$
$$M = \sum_{\lambda=380}^{780} \Phi(\lambda)M(\lambda)$$
$$S = \sum_{\lambda=380}^{780} \Phi(\lambda)S(\lambda)$$



Matrix Perspective

$$L = \sum_{\lambda=380}^{780} \Phi(\lambda)L(\lambda)$$

$$M = \sum_{\lambda=380}^{780} \Phi(\lambda)M(\lambda)$$

$$S = \sum_{\lambda=380}^{780} \Phi(\lambda)S(\lambda)$$

$$\begin{bmatrix} L_{380}, L_{381}, \dots, L_{780} \\ M_{380}, M_{381}, \dots, M_{780} \\ S_{380}, S_{381}, \dots, S_{780} \end{bmatrix} \times \begin{bmatrix} \Phi_{380} \\ \Phi_{381} \\ \vdots \\ \Phi_{780} \end{bmatrix} = \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

Matrix Perspective

- It's an under-determined system of linear equations. In general, it has infinitely many solutions.
- In general, there are infinitely many lights that correspond to the same color. This is called **metamerism**. More on this soon.

An additional constraint: Φ must all be non-negative, since there is no negative power!

$$\begin{bmatrix} L_{380}, L_{381}, \dots, L_{780} \\ M_{380}, M_{381}, \dots, M_{780} \\ S_{380}, S_{381}, \dots, S_{780} \end{bmatrix} \times \begin{bmatrix} \Phi_{380} \\ \Phi_{381} \\ \vdots \\ \Phi_{780} \end{bmatrix} = \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

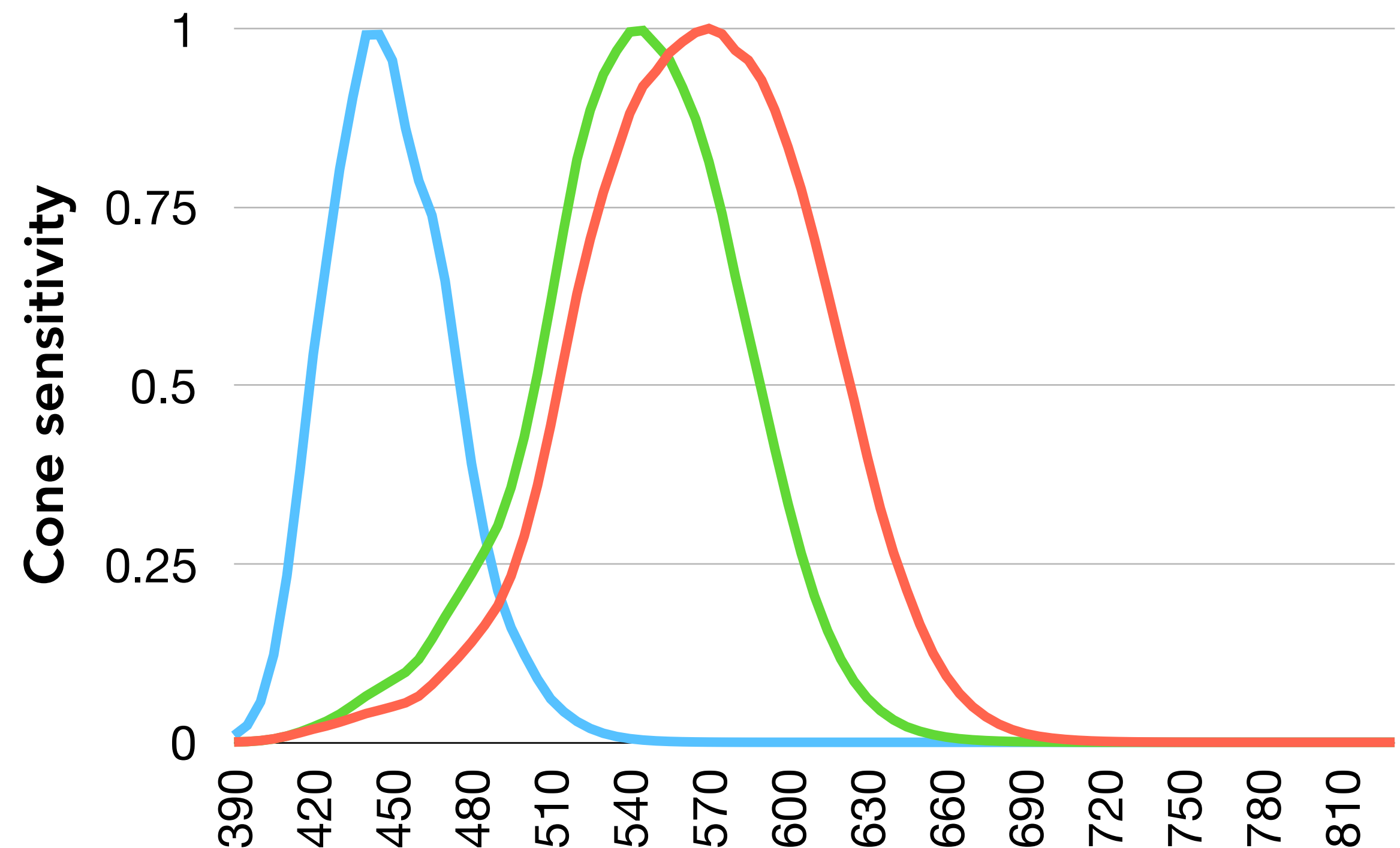
The first matrix is known. Given the [L, M, S] vector, can you solve for the Φ vector?

But Can There Be No Solution?

- One scenario: negative L , M , or S responses. All cone responses are physical quantities, which must be positive.

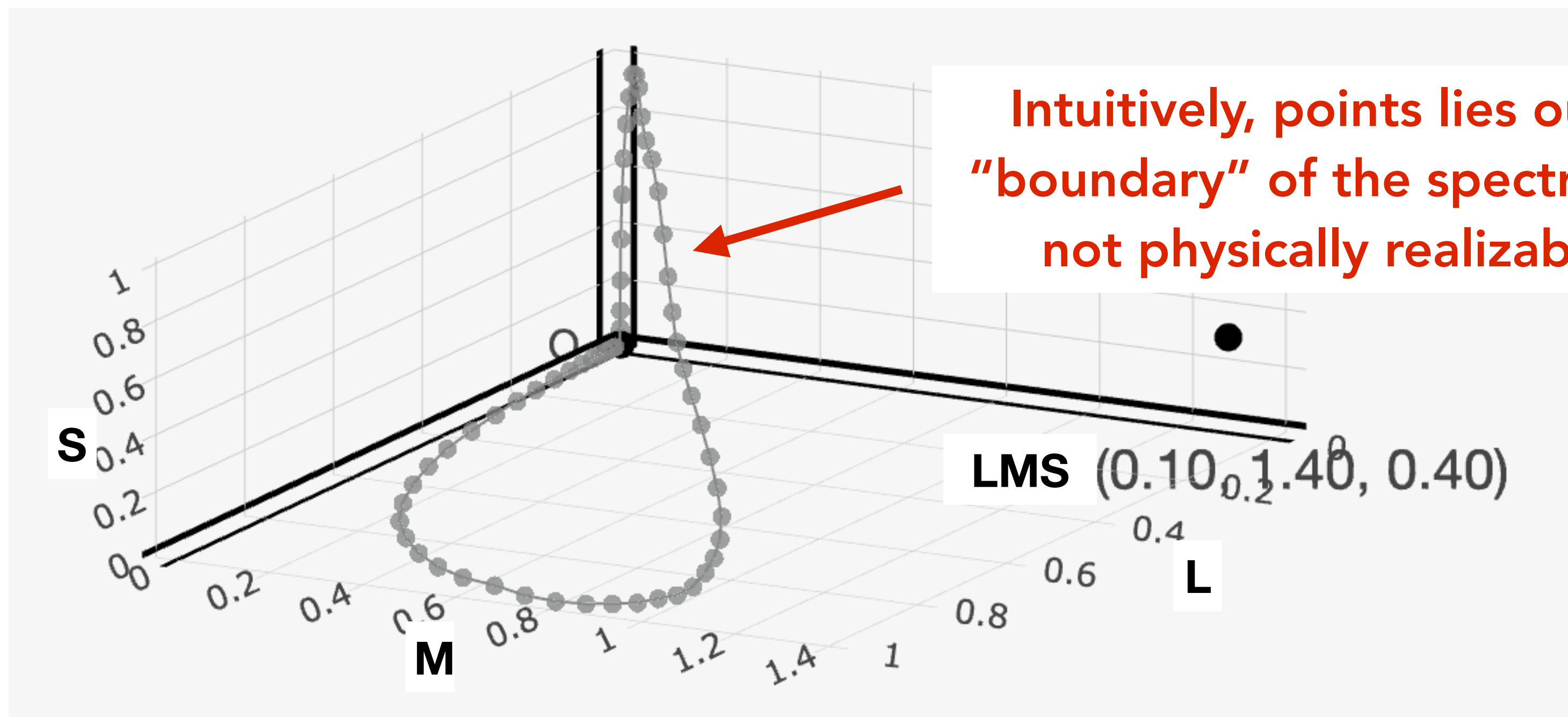
But Can There Be No Solution?

- Another scenario: impossible cone response combinations.
 - E.g., $[1, 0, 0]$: there is no real light that can produce only L cone response but no responses from M and S cones.
 - Except when...



But Can There Be No Solution?

- Another scenario: impossible cone response combinations.
 - An impossible cone combination still corresponds to a point in the LMS space. We call it an imaginary color. It's not a color that can be produced by physical lights.



Play with an interactive app here: <https://horizon-lab.org/colorvis/chromaticity.html>

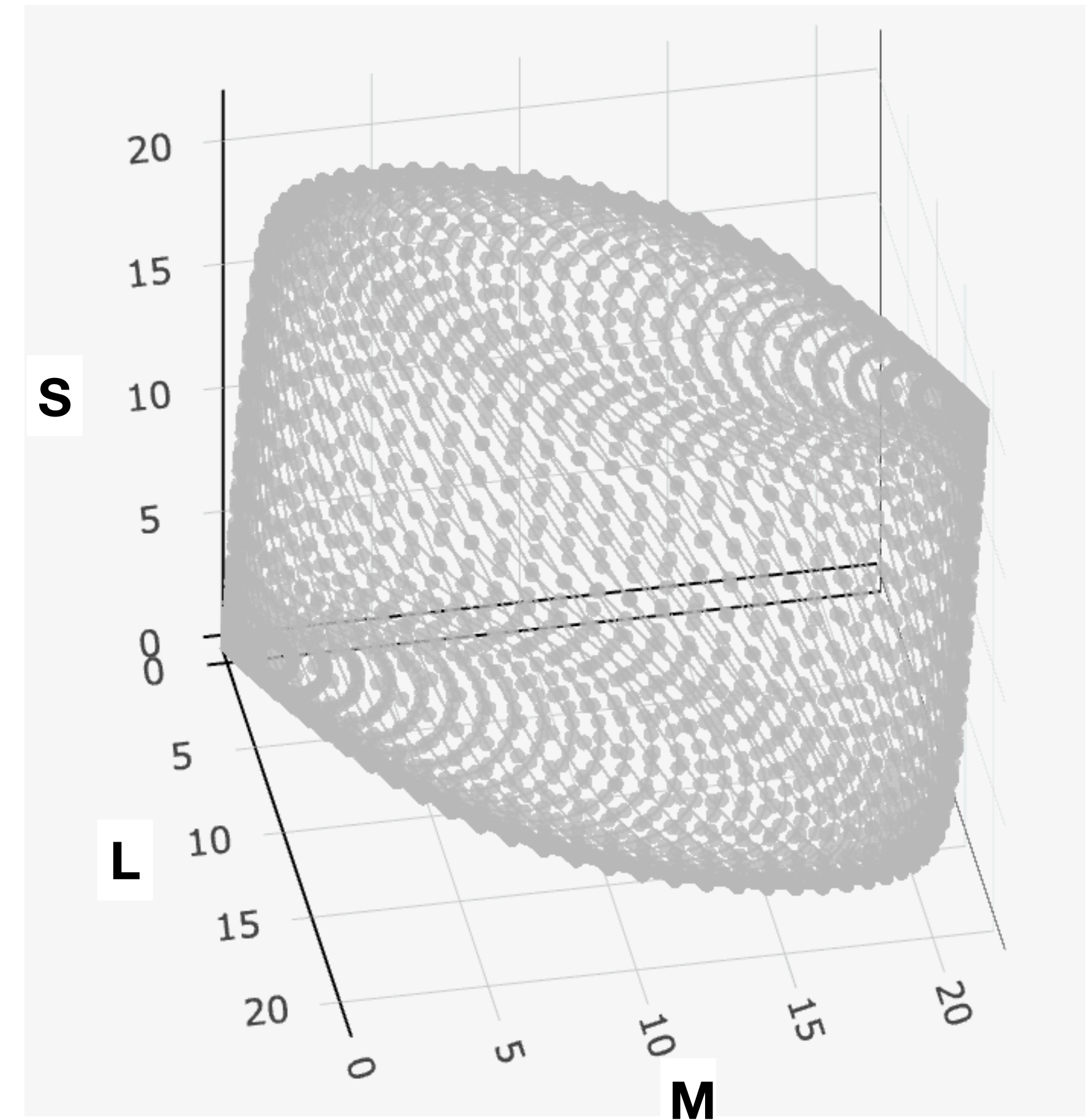
Color Gamut of Human Visual System (HVS)

- HVS Color Gamut: the set of all the colors that human can see.
- The HVS color gamut encapsulates all the LMS points for which the system of linear equations below has a non-negative solution.

$$\begin{bmatrix} L_{380}, L_{381}, \dots, L_{780} \\ M_{380}, M_{381}, \dots, M_{780} \\ S_{380}, S_{381}, \dots, S_{780} \end{bmatrix} \times \begin{bmatrix} \Phi_{380} \\ \Phi_{381} \\ \vdots \\ \Phi_{780} \end{bmatrix} = \begin{bmatrix} L \\ M \\ S \end{bmatrix}$$

Visualizing HVS Gamut

- See visualization here: <https://horizon-lab.org/colorvis/gamutvis.html>.
- In reality, the gamut has no boundary, since we can arbitrarily increase the light power and this 3D volume will extend to infinity.

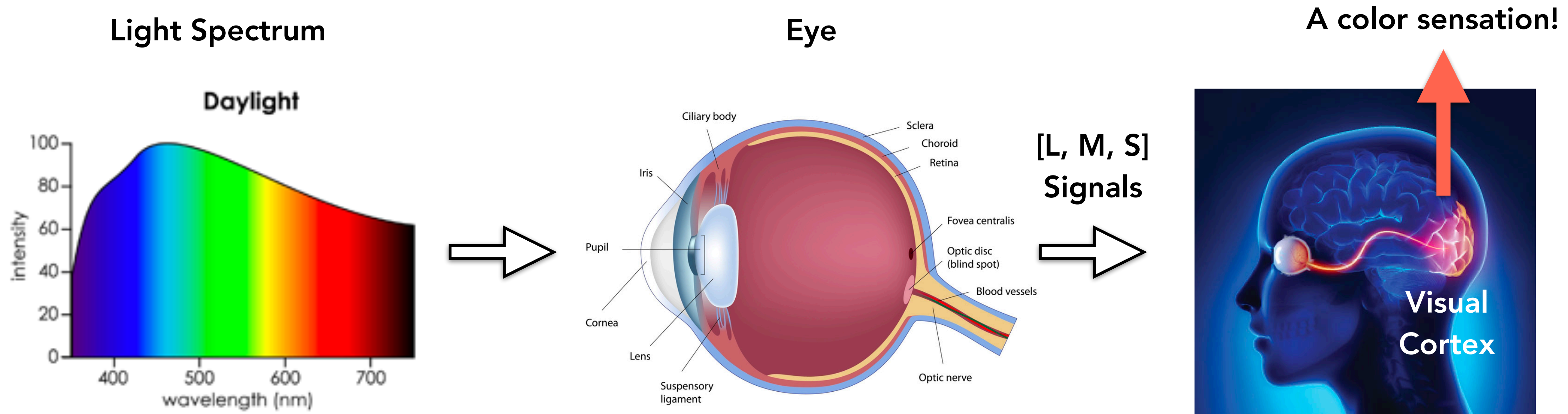


Two Fascinating Questions

- 1. Does any arbitrary point in the LMS space correspond to a color?
 - No
- 2. Will there be multiple lights that correspond to the same point, i.e., color in the LMS space?
 - Yes. In fact, there are infinitely many.

Color Matching Experiments and Metamerism

Intuition



- Lights that produce the same LMS signals are *perceived* by the brain as the same "color", even if their spectra might be totally different!
- ...because retinal processing is a dramatic dimensionality reduction.

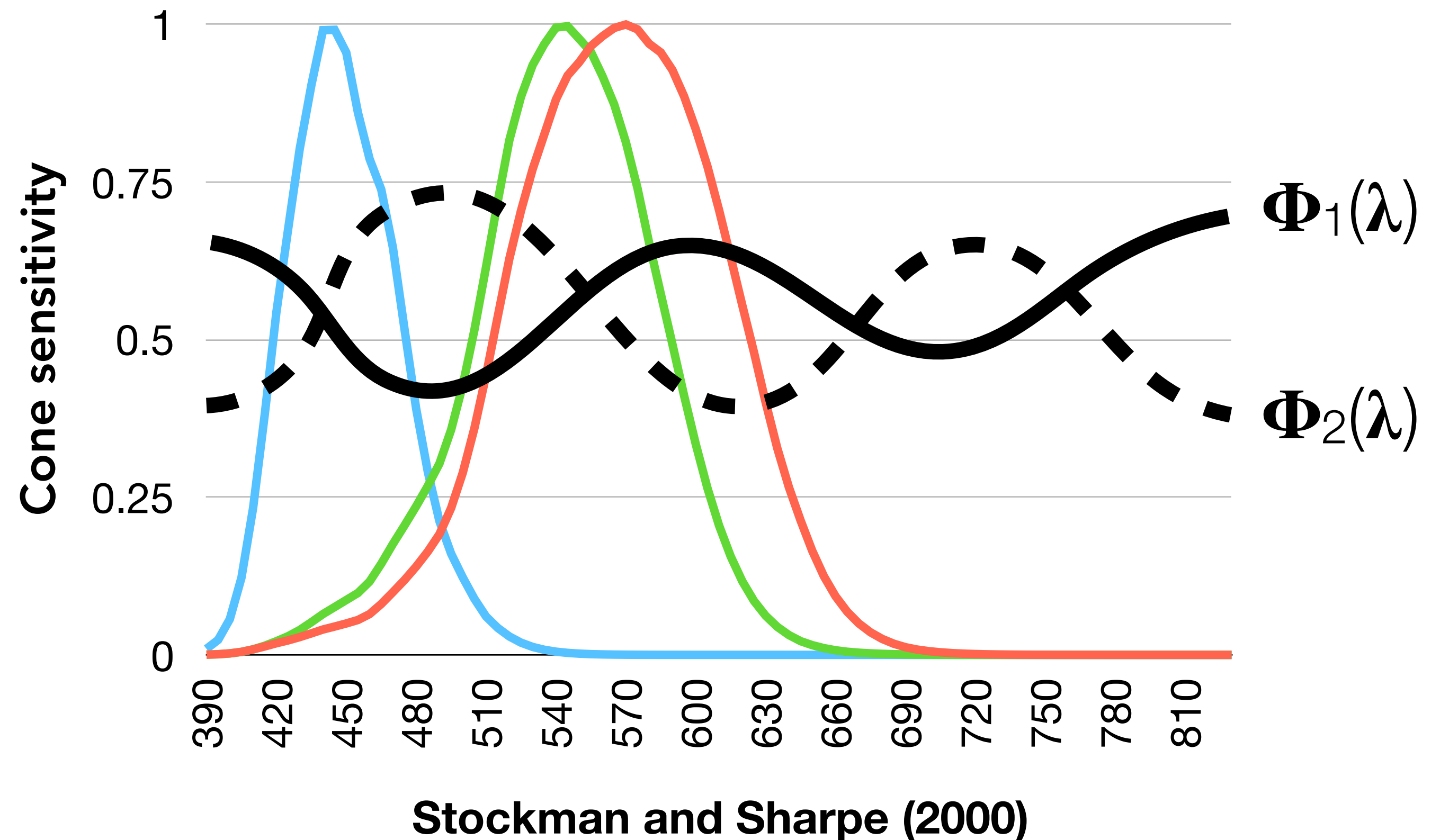
Metamerism

- The two lights are metamers of each other (i.e., seen as having the same color) if their LMS cone responses match.

$$\sum_{\lambda} \Phi_1(\lambda)L(\lambda) = \sum_{\lambda} \Phi_2(\lambda)L(\lambda)$$

$$\sum_{\lambda} \Phi_1(\lambda)M(\lambda) = \sum_{\lambda} \Phi_2(\lambda)M(\lambda)$$

$$\sum_{\lambda} \Phi_1(\lambda)S(\lambda) = \sum_{\lambda} \Phi_2(\lambda)S(\lambda)$$



Metamerism

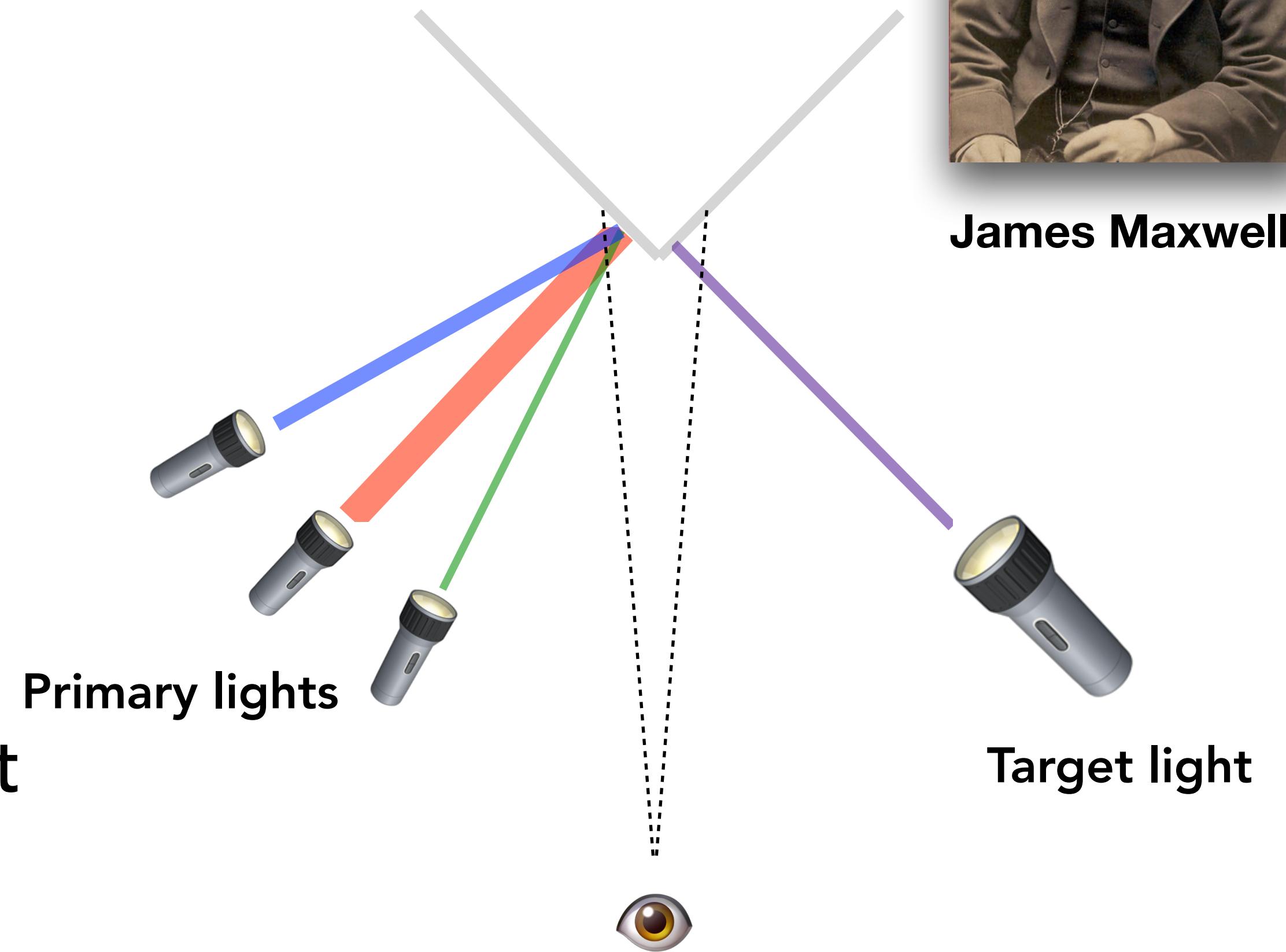
- Does metamerism exist? That is, given a spectrum Φ , can we always find at least one Φ' that is the metamer of Φ ? Can we find multiple?
- The answer is yes. We showed earlier how to find metamers by solving system of linear equations. But that requires knowing $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$, which were not measured until after 1900s
 - we've talked before about how they are measured
- But people were able to find metamers as early as late 19th century, through a clever *color matching* experiment.

Color Matching Experiments

- You are given three monochromatic (spectral) lights with known spectra pointing to the same point.
 - They are called the *primary lights*.
- You are also given a target light with unknown spectrum.
- Tune each primary light's power so that the color of the primary light mix matches the color of the target light.



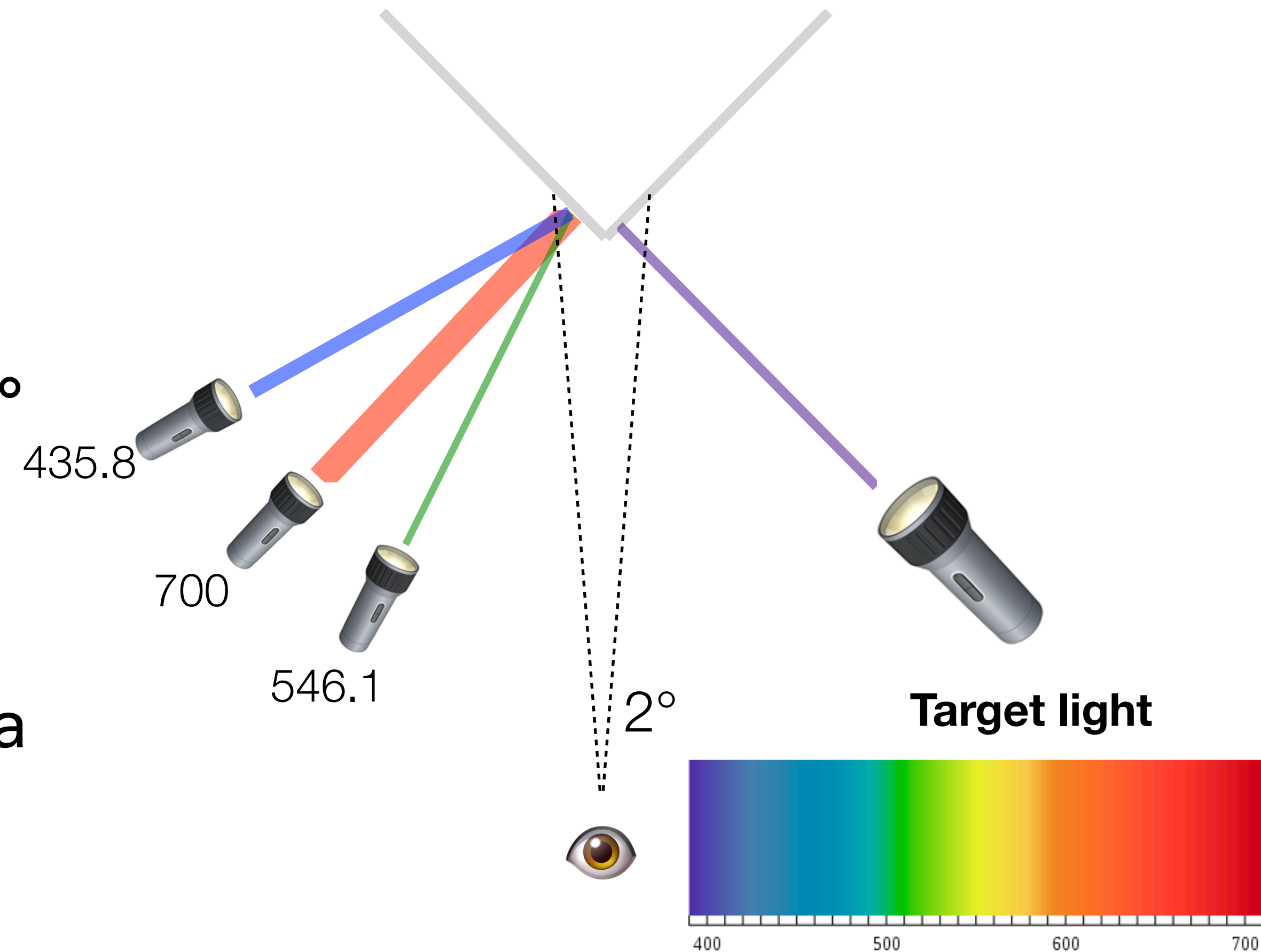
James Maxwell



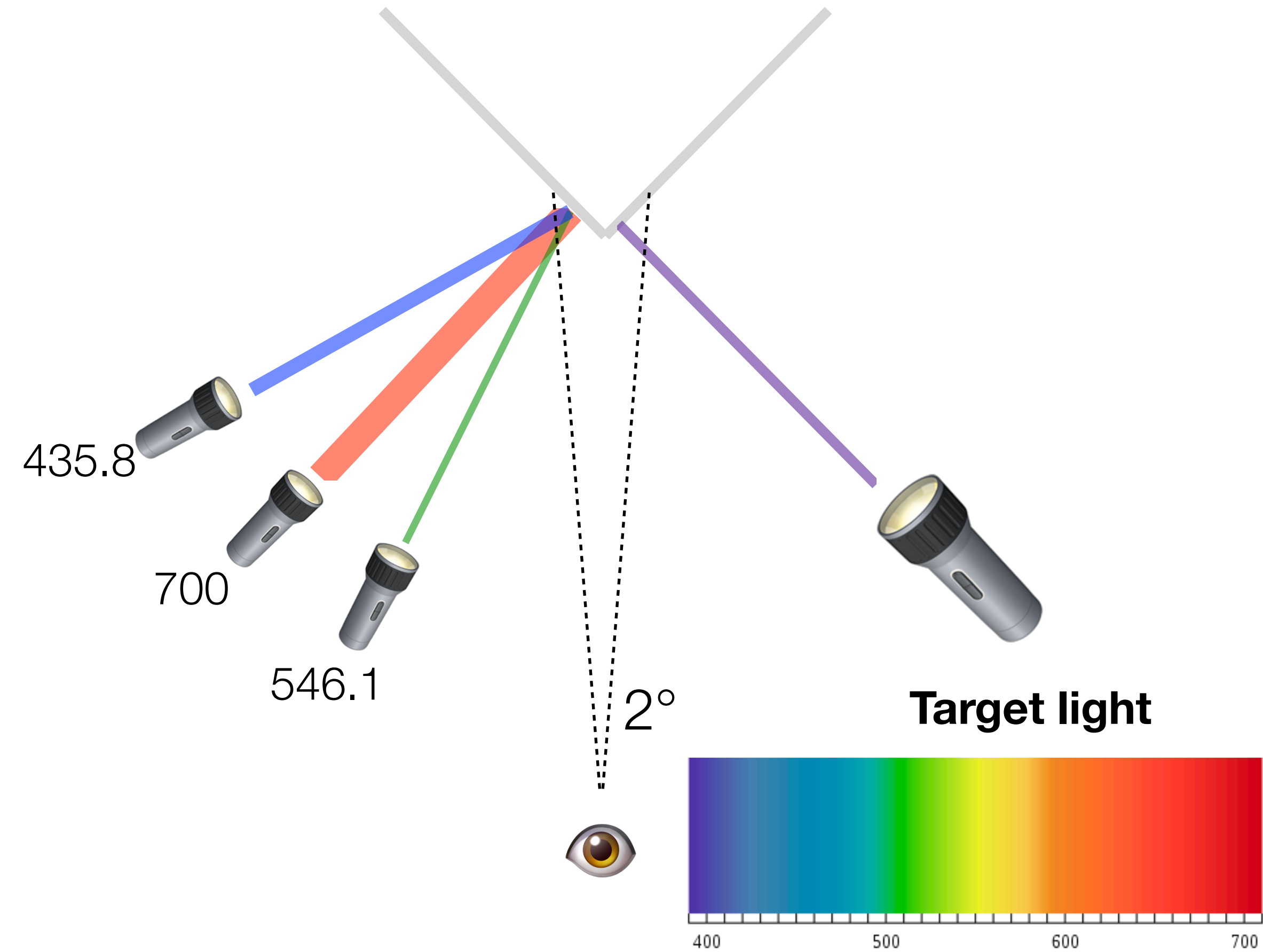
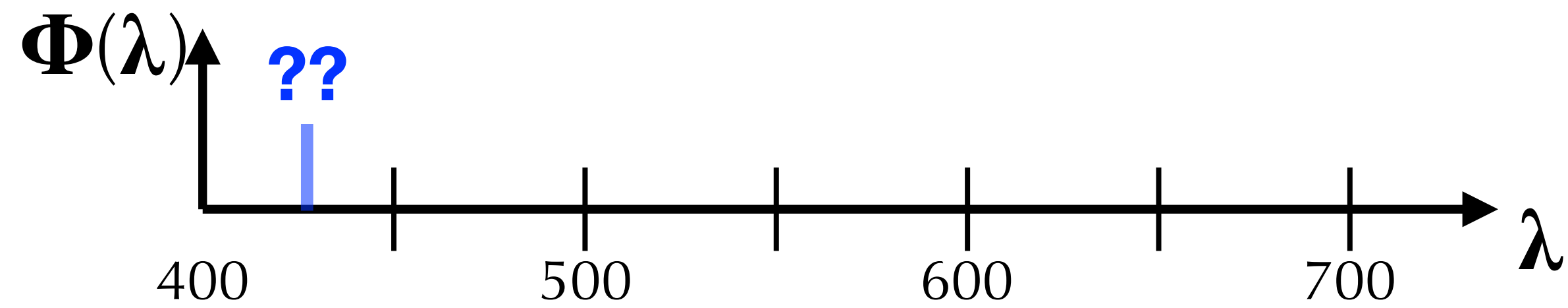
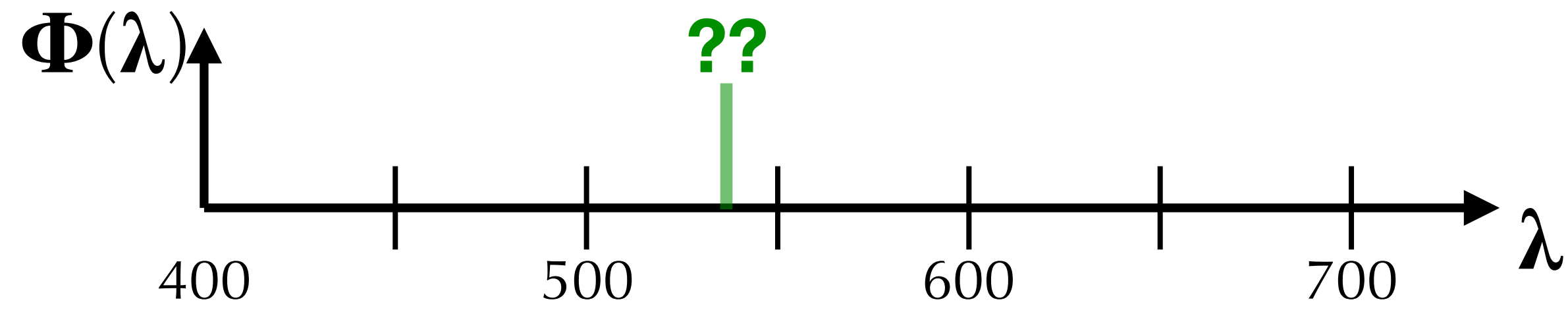
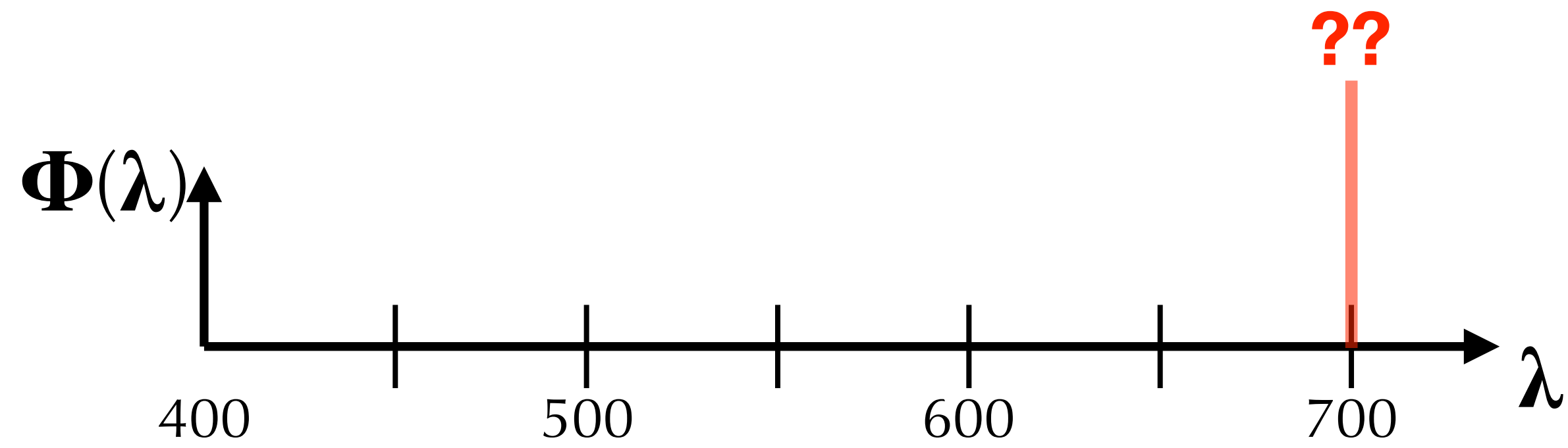
Color matching experiment; circa 1835

Color Matching Experiments

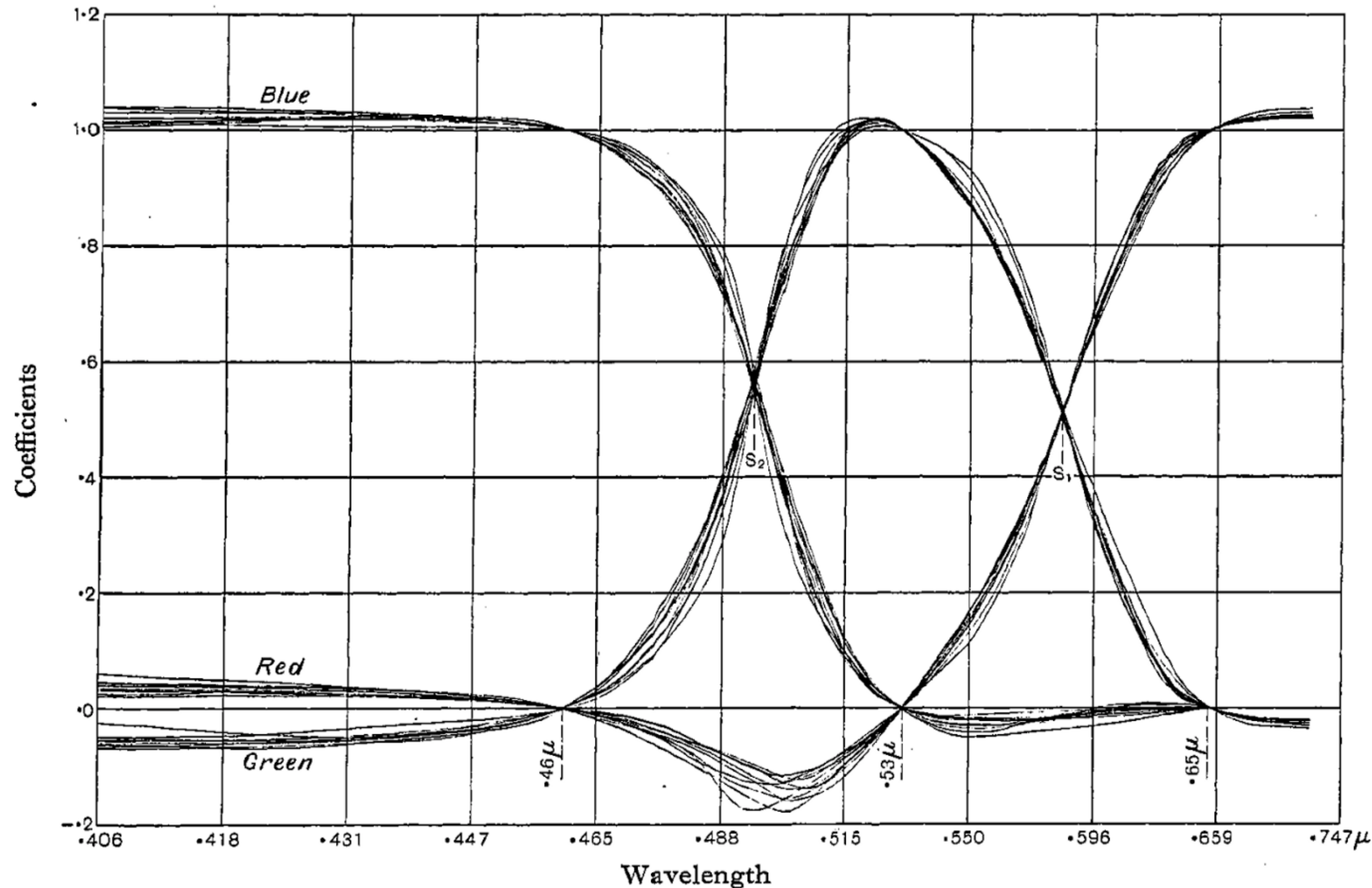
- The three primary lights used in CIE 1931 standard: $\lambda=435.8$ nm, 546.1 nm, 700 nm; roughly blue, green, and red.
- CIE 1931 limited viewing angle to be 2° so that only the fovea gets light.
- It swept all the spectral lights in the visible spectrum as the target light (at a 5-nm interval).



Color Matching Experiments



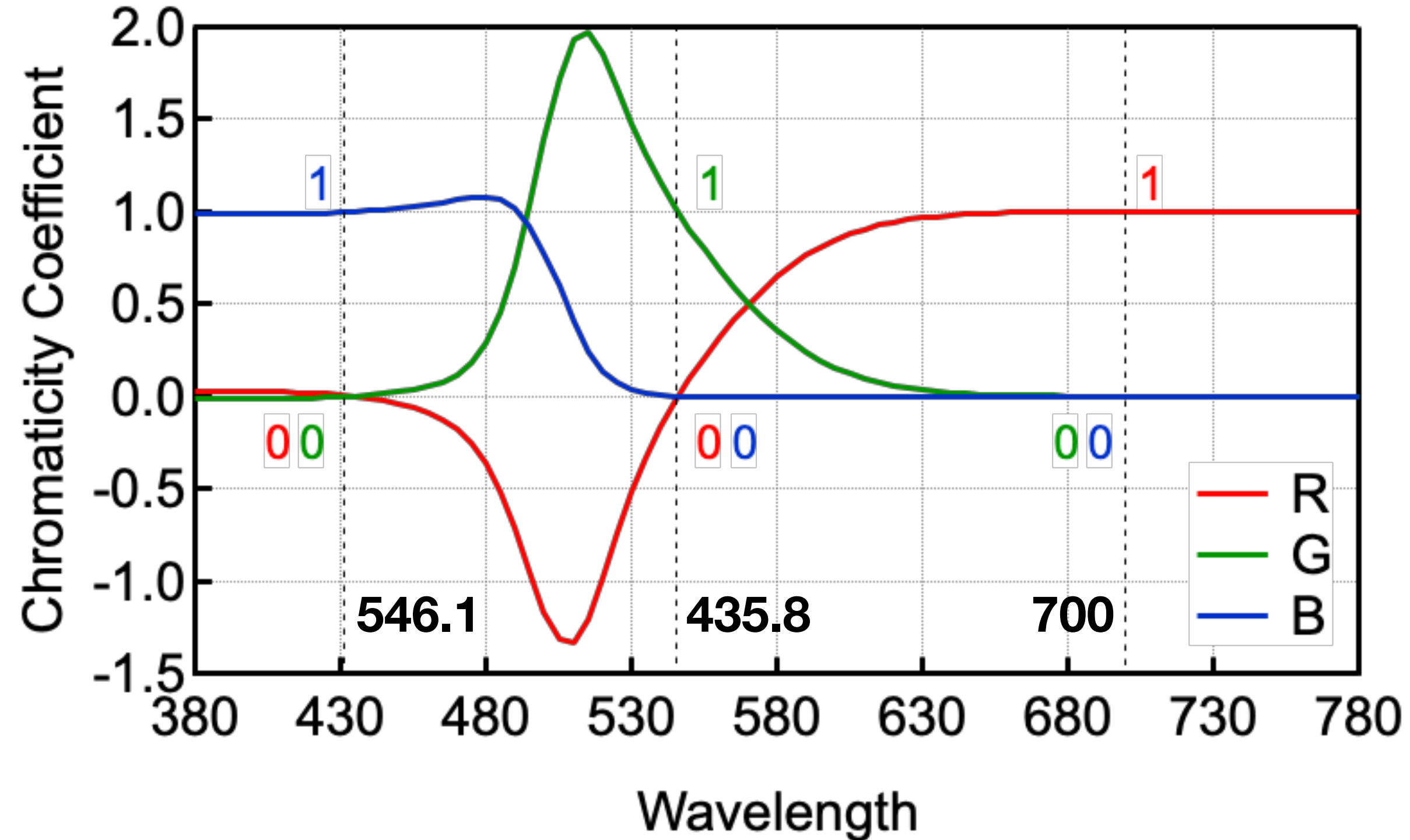
Color Matching Experiments By Wright and Guild



- Wright and Guild did two separate color matching experiments in the late 1920s
- They used primaries and white point different from the CIE standard.
- This is the results of Wright's experiment.
- Their data eventually were turned into CIE data.

CIE 1931 Color Matching Experiments

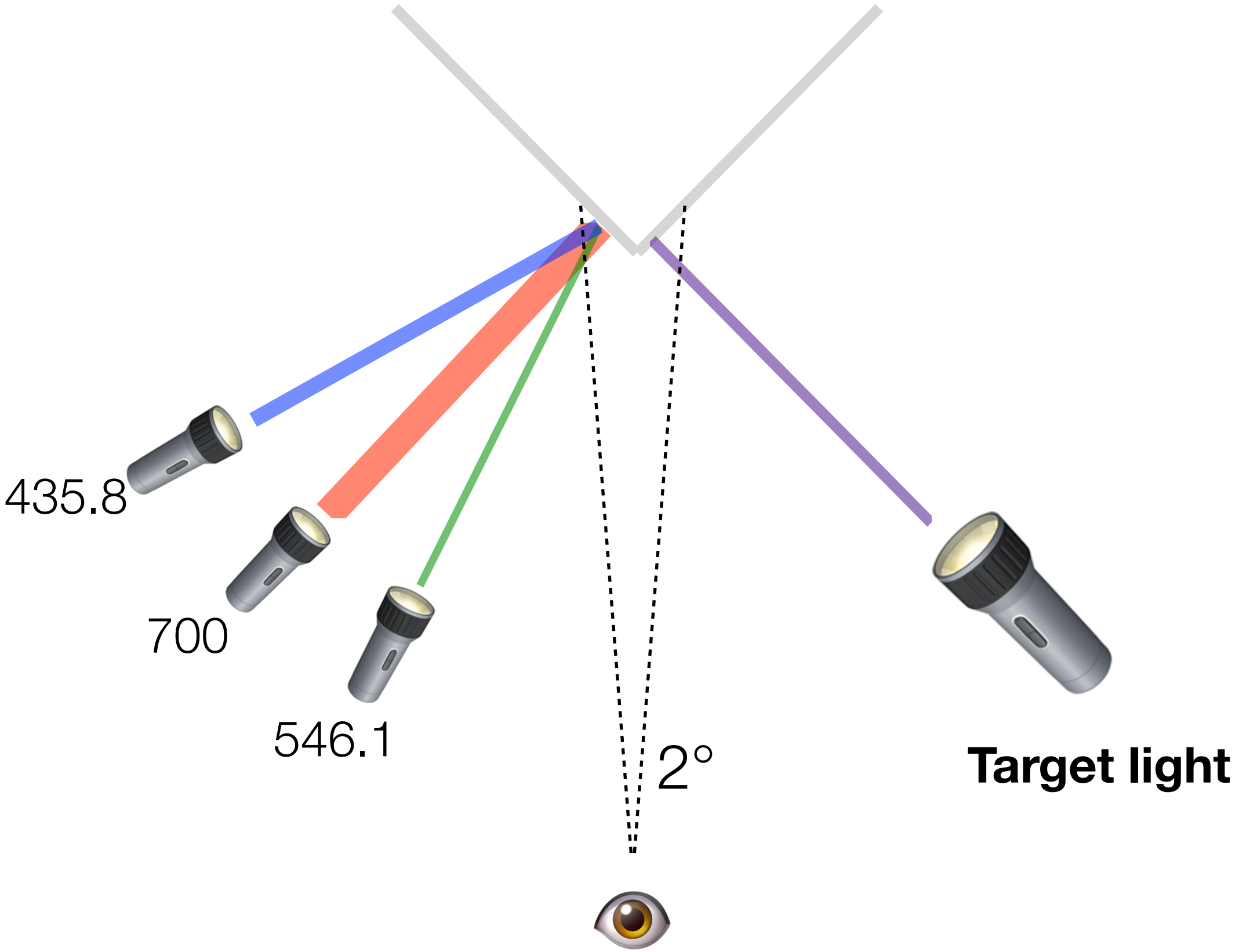
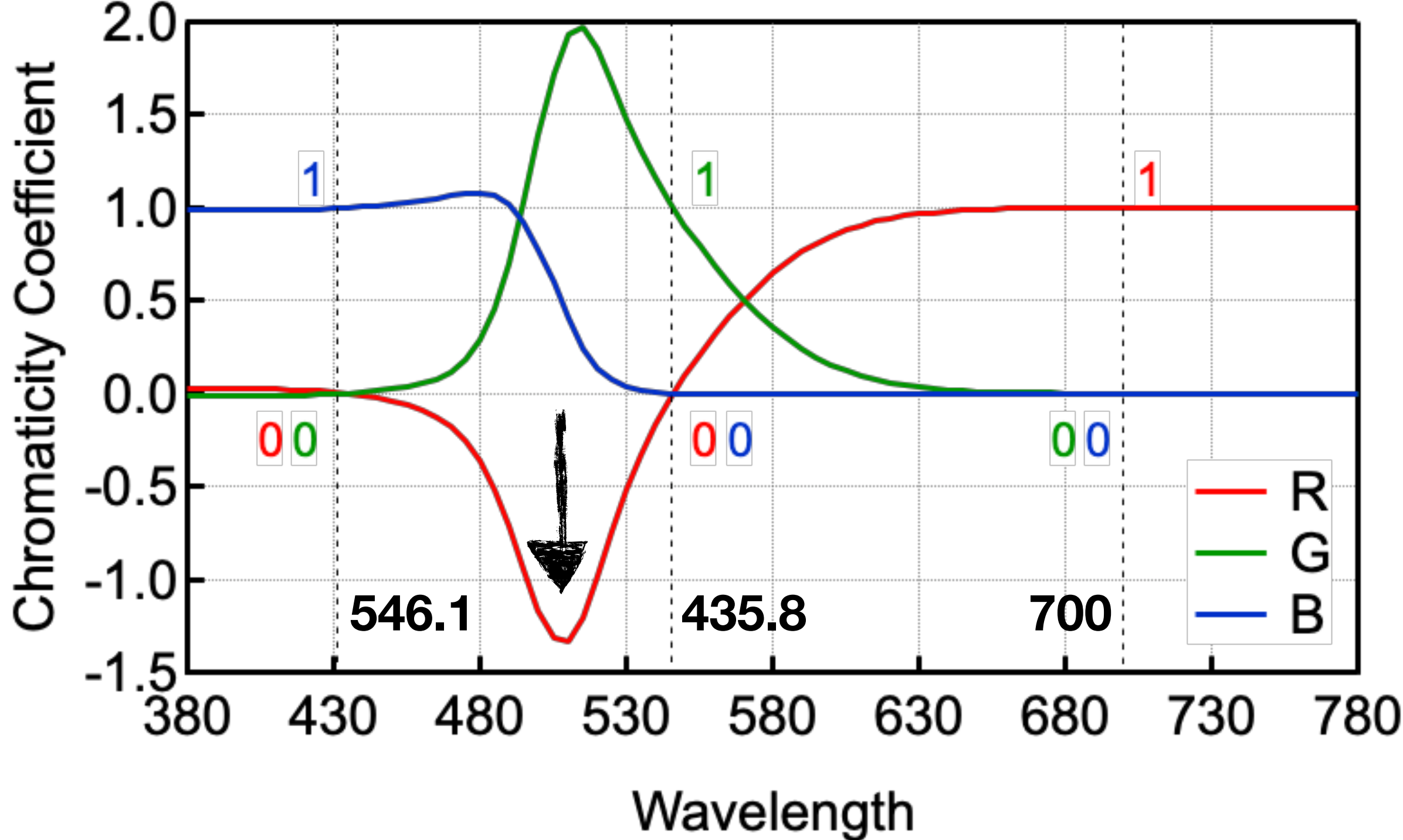
Record the units of primary lights and normalize them so that they add up to 1.



- Y-axis is the "amount" of each of the primary.
- The unit system is so defined that mixing equal amount of primaries produces the color of the "equal-energy white", whose SPD is a constant at all wavelengths.
- Different color spaces can choose different white points. More later.

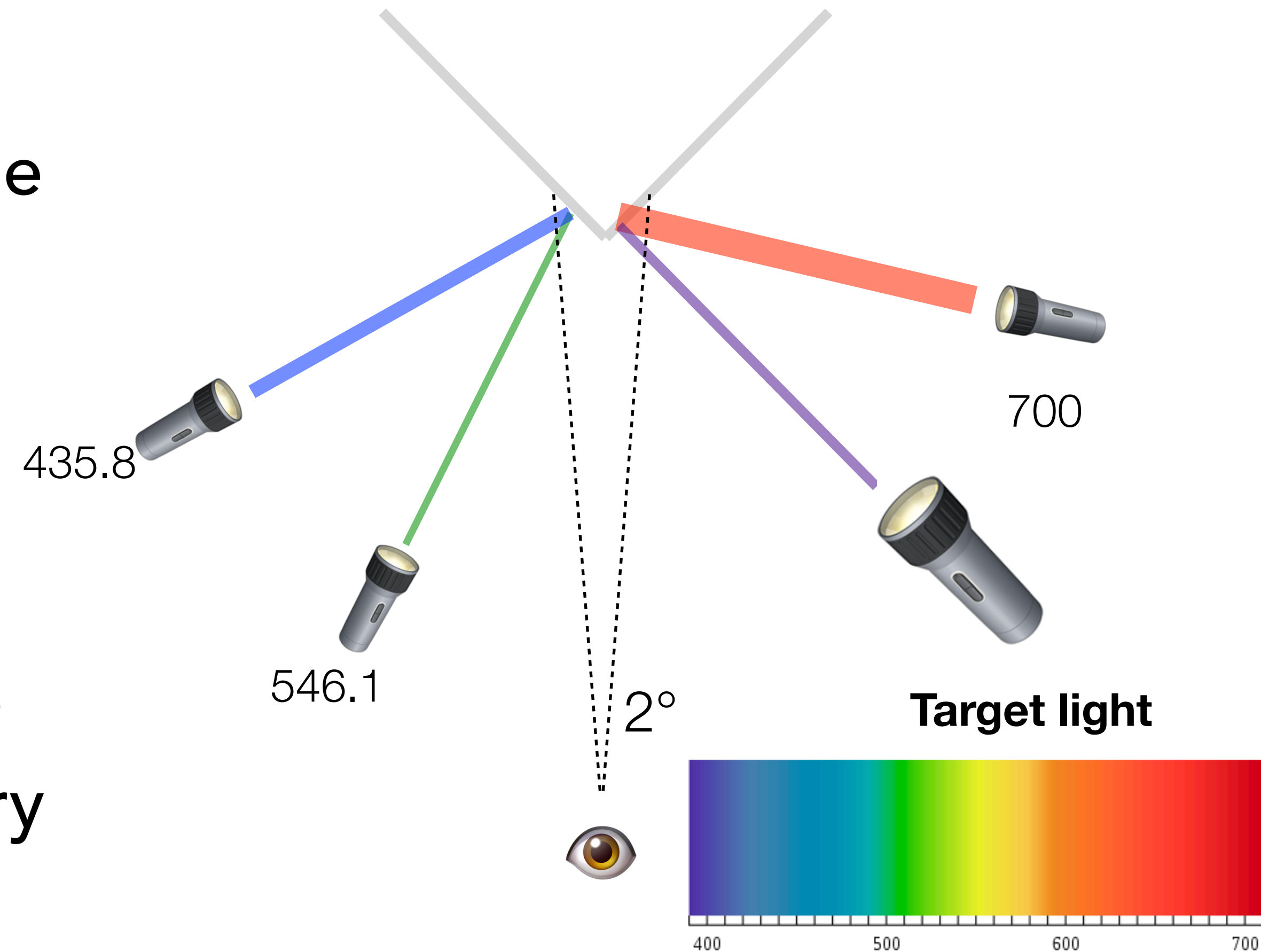
Negative Color?

To match color of $\lambda=500$ nm, we need a bit of negative red? What does this mean???

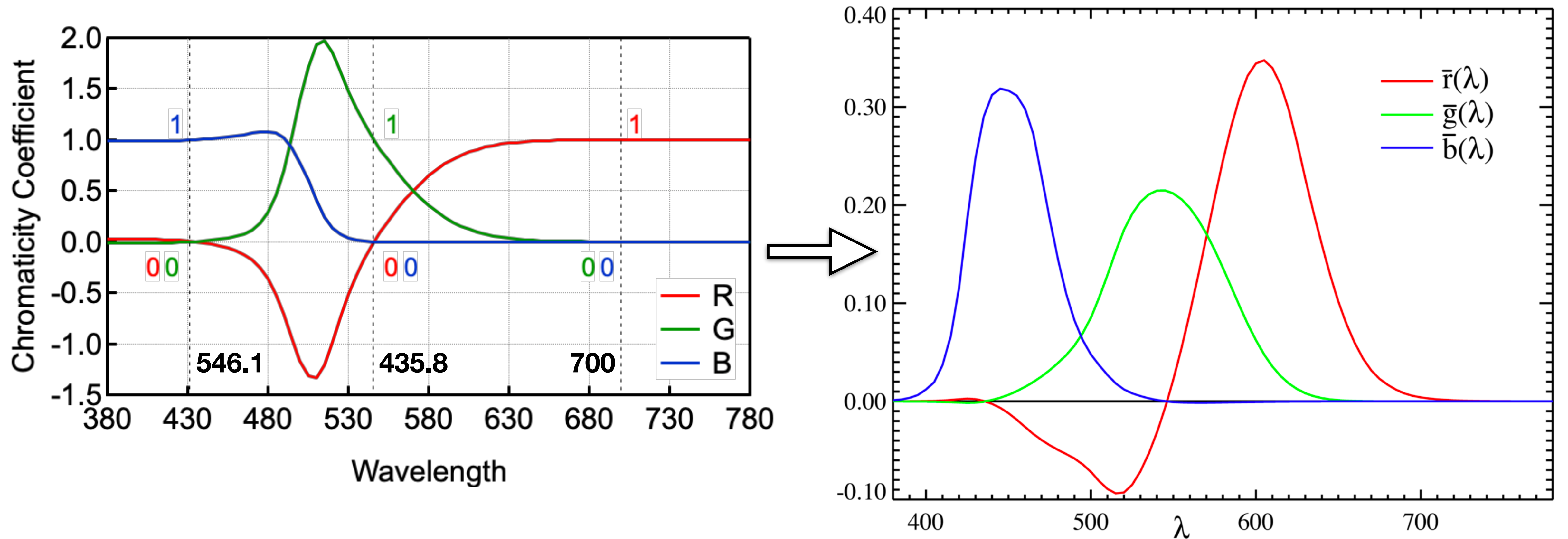


Negative Values in Color Matching Functions

- No combination of RGB matches the target light, but adding some R with the target light matches the color of some combination of G and B.
- Color of light $\lambda=540$ nm can't be reproduced by R, G, B. Doesn't mean $\lambda=540$ nm doesn't exist; it just can't be generated from the three chosen primary lights. More later (gamut).



Normalization



The plot on the left gives the relative ratio of the primaries, the plot on the right gives the absolute amount, scaled from the left to match the luminance at each wavelength.

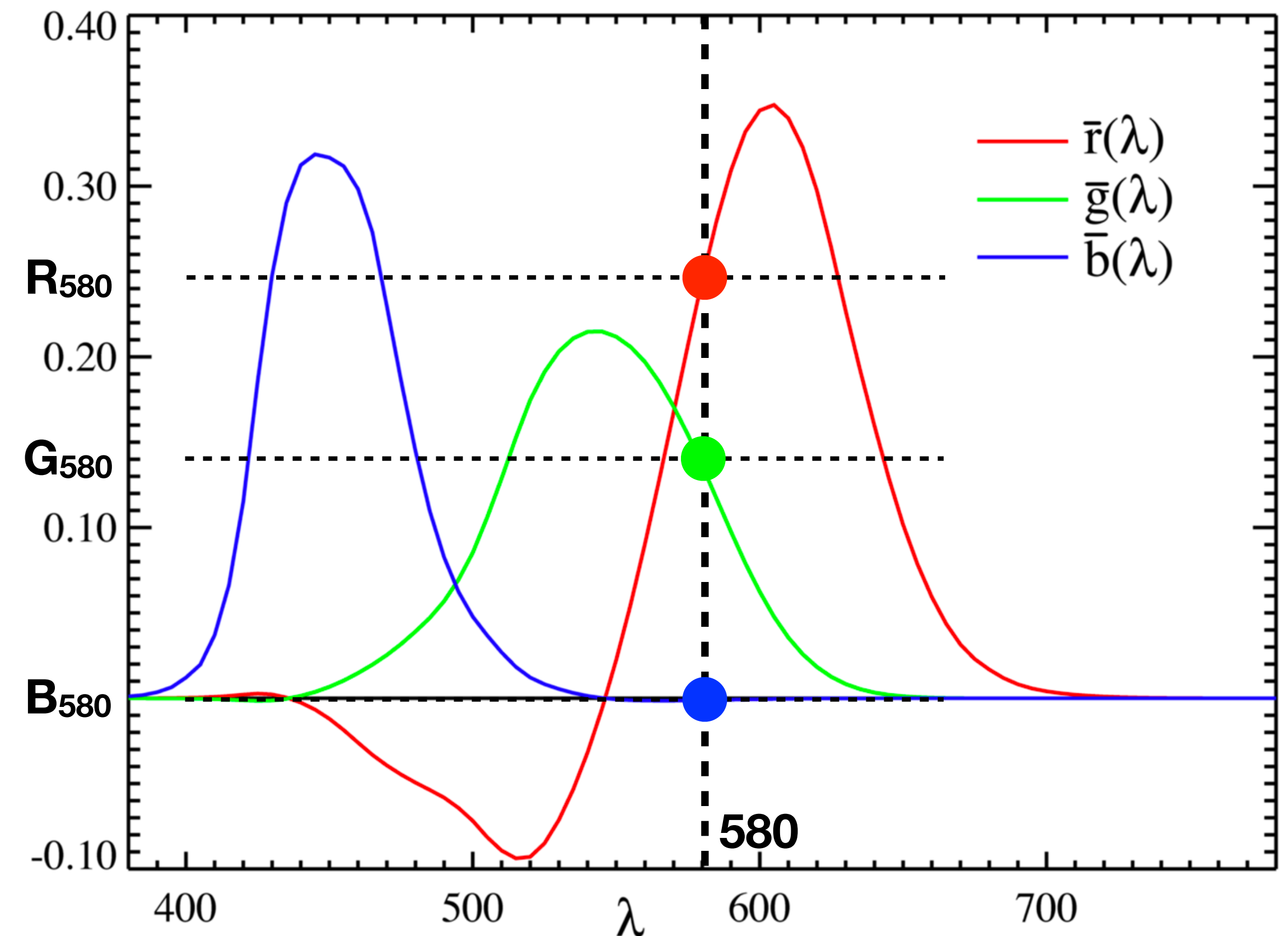
See: <https://yuhaozhu.com/blog/cmf.html>.

The Results are the Color Matching Functions

- For one unit power of each target light, how many units of each primary light are needed to match the color.
- RGB values of a target color are called the **tristimulus values** of the color in the CIE 1931 RGB color space.

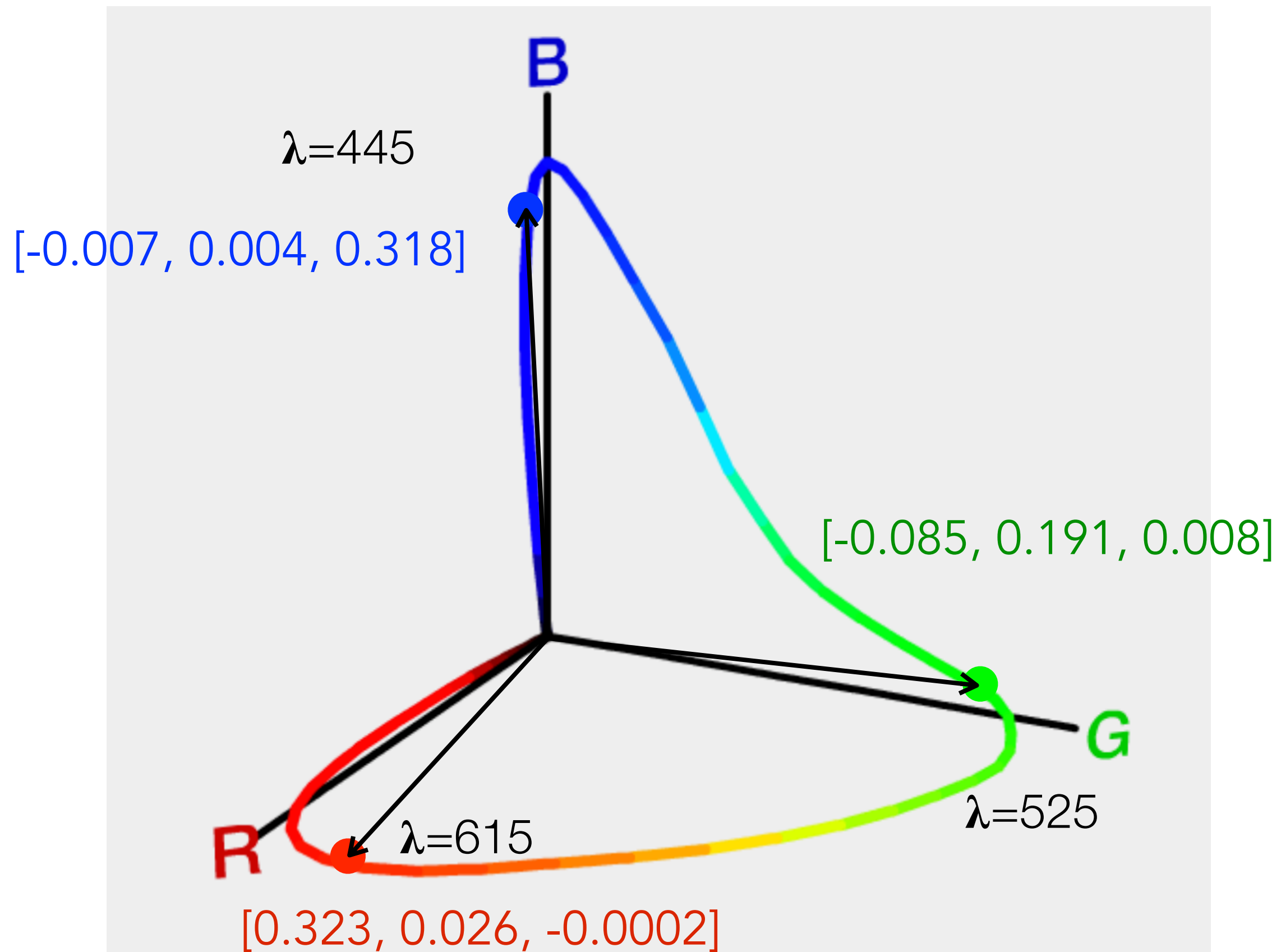
If the target light λ has a power of Φ_{580} , the amounts of the primary lights we need are:

$$\Phi_{580} \times \mathbf{R}_{580}, \quad \Phi_{580} \times \mathbf{G}_{580}, \quad \Phi_{580} \times \mathbf{B}_{580}$$

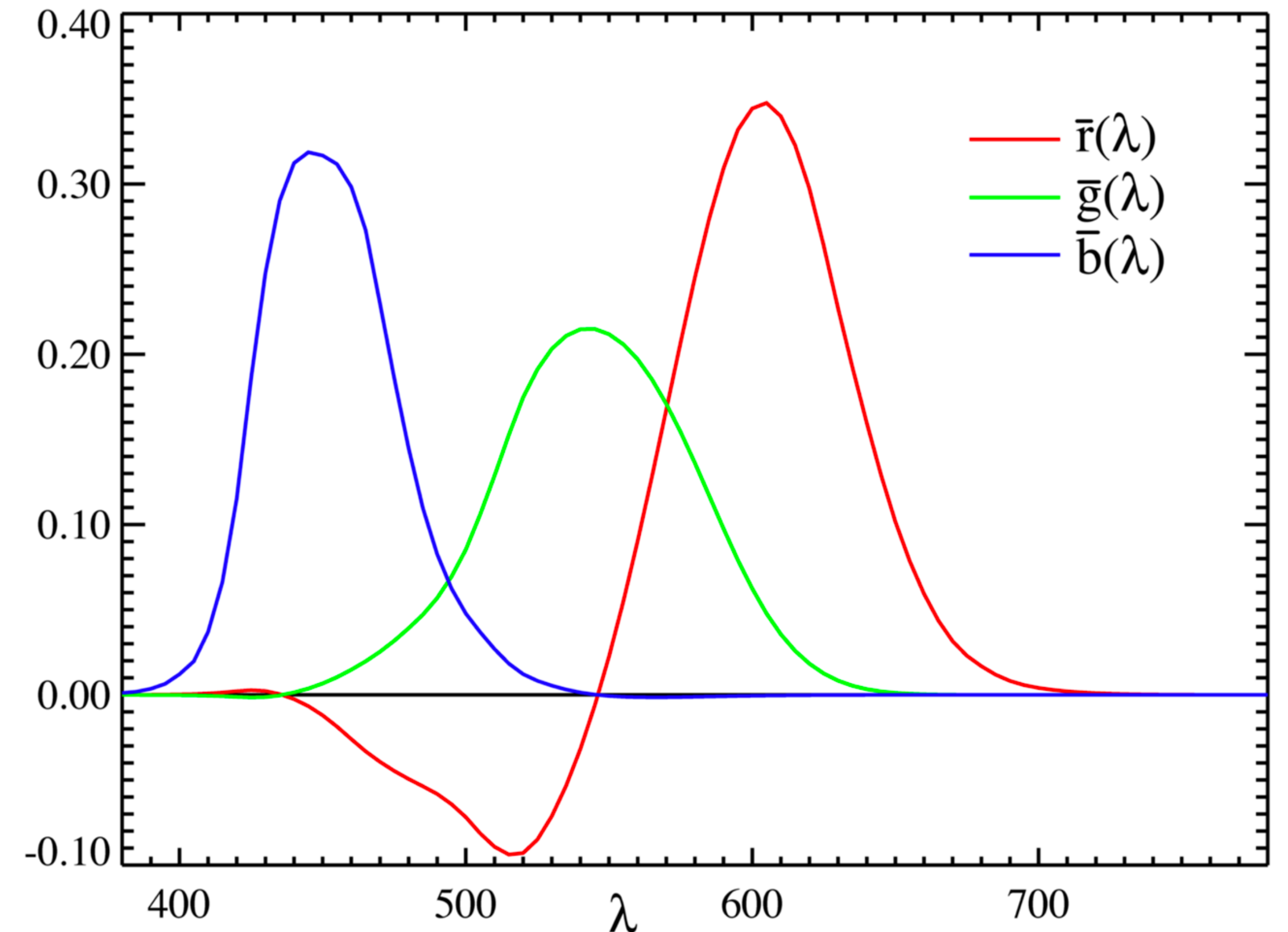


CIE 1931 2° RGB Color Matching Functions

Spectral Locus in the CIE 1931 RGB Space



Spectral locus in CIE 1931 RGB



CIE 1931 2° RGB Color Matching Functions

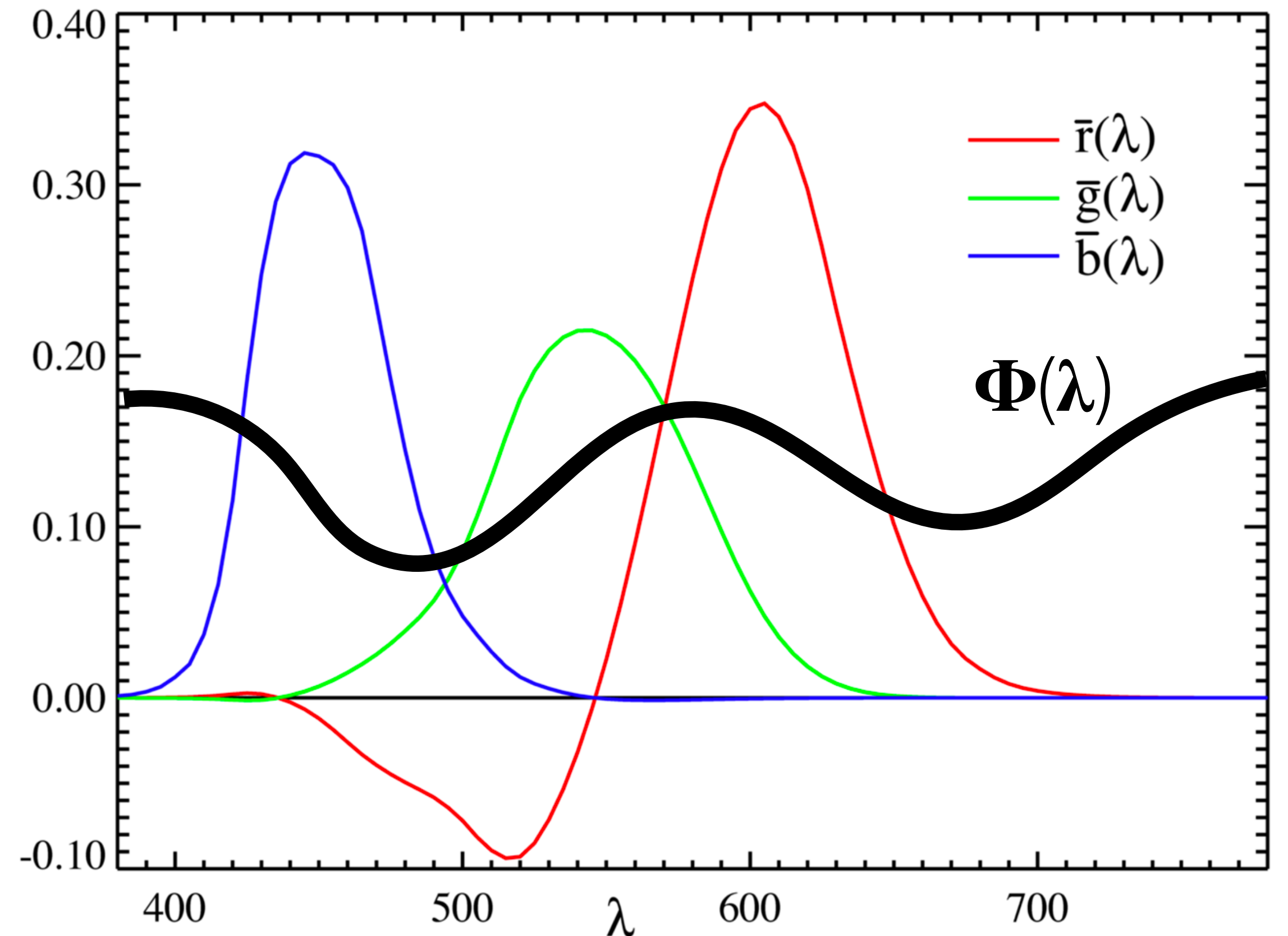
Expressing Arbitrary Light Using CMFs

- How much total R, G, and B primaries are needed to match the color of an arbitrary light Φ ?
- Calculate it wavelength-by-wavelength and sum it up.

$$R = \sum_{\lambda} \Phi(\lambda) \bar{r}(\lambda)$$

$$G = \sum_{\lambda} \Phi(\lambda) \bar{g}(\lambda)$$

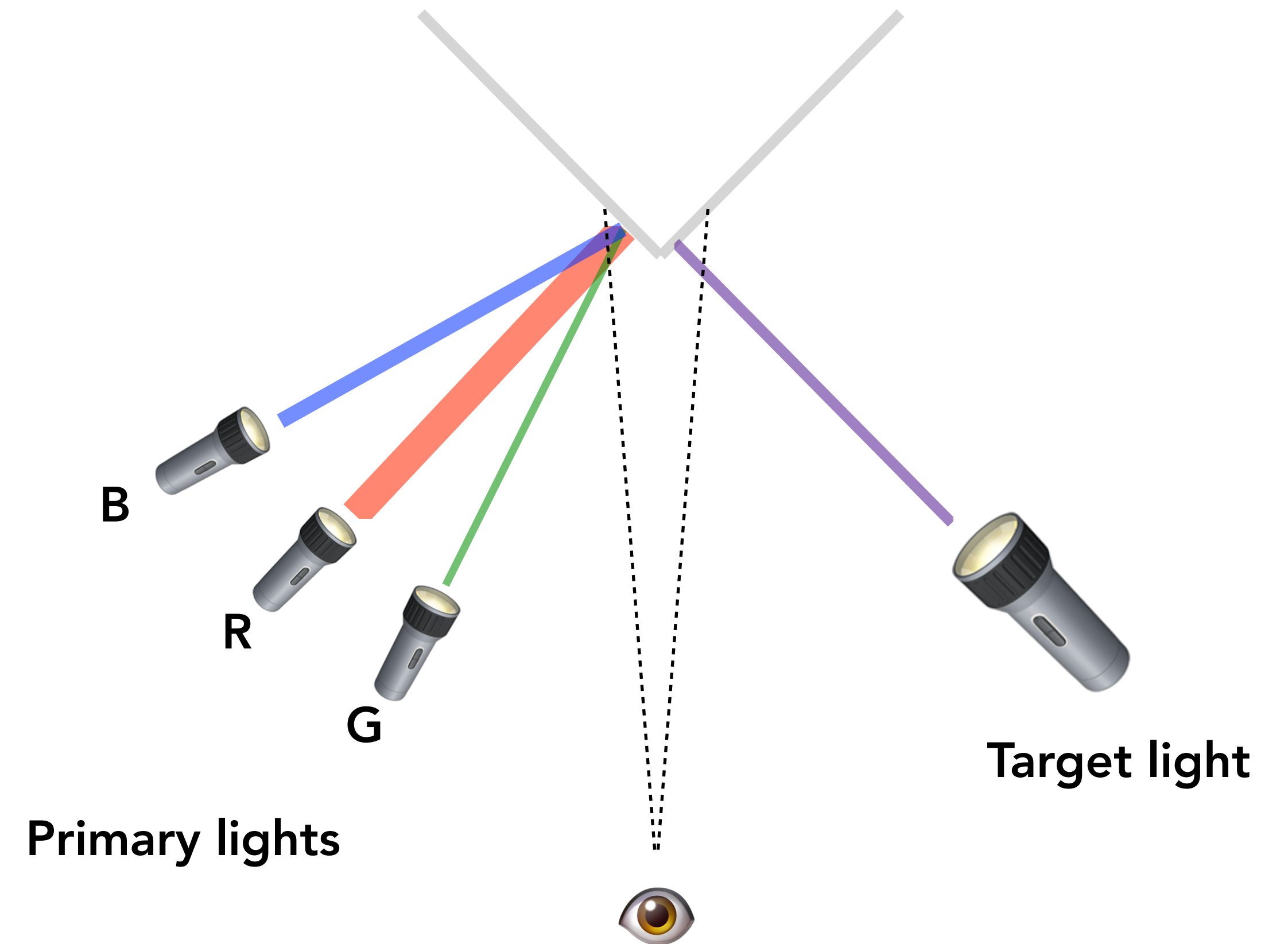
$$B = \sum_{\lambda} \Phi(\lambda) \bar{b}(\lambda)$$



CIE 1931 2° RGB Color Matching Functions

How To Explain Color Matching Experiments?

- Given a target light $\Phi(\lambda)$ and the primary lights, can we calculate the tristimulus values for $\Phi(\lambda)$ *without* the color matching experiment?
- Key: the total L, M and S cone responses of the three primary lights must match the total cone responses of the target light.



Intuition

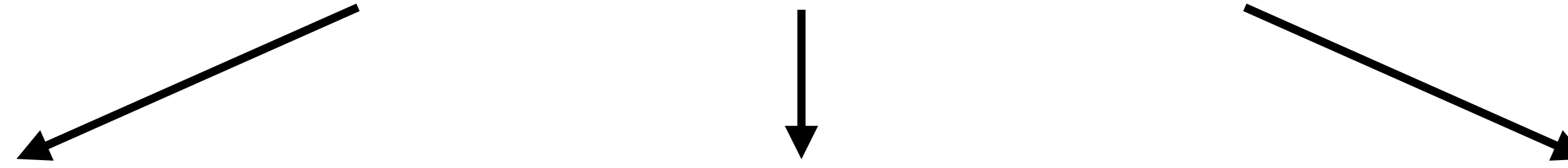
**L cone response of target light = L cone response of primary R
+ L cone response of primary G
+ L cone response of primary B**

**M cone response of target light = M cone response of primary R
+ M cone response of primary G
+ M cone response of primary B**

**S cone response of target light = S cone response of primary R
+ S cone response of primary G
+ S cone response of primary B**

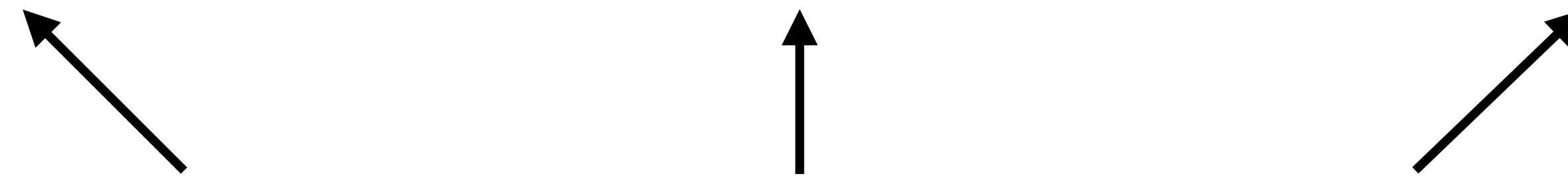
Matching L Cone Responses

Amount of primary lights needed (unknown)



$$= \sum \Phi(\lambda)L(\lambda)$$

Amount of L cone responses of one unit of each primary light



The L cone response of the target light

Matching All Cone Responses

$$\sum R(\lambda)L(\lambda) \times r + \sum G(\lambda)L(\lambda) \times g + \sum B(\lambda)L(\lambda) \times b = \sum \Phi(\lambda)L(\lambda)$$

$$\sum R(\lambda)M(\lambda) \times r + \sum G(\lambda)M(\lambda) \times g + \sum B(\lambda)M(\lambda) \times b = \sum \Phi(\lambda)M(\lambda)$$

$$\sum R(\lambda)S(\lambda) \times r + \sum G(\lambda)S(\lambda) \times g + \sum B(\lambda)S(\lambda) \times b = \sum \Phi(\lambda)S(\lambda)$$

Equivalent to Solving a System of Linear Equations

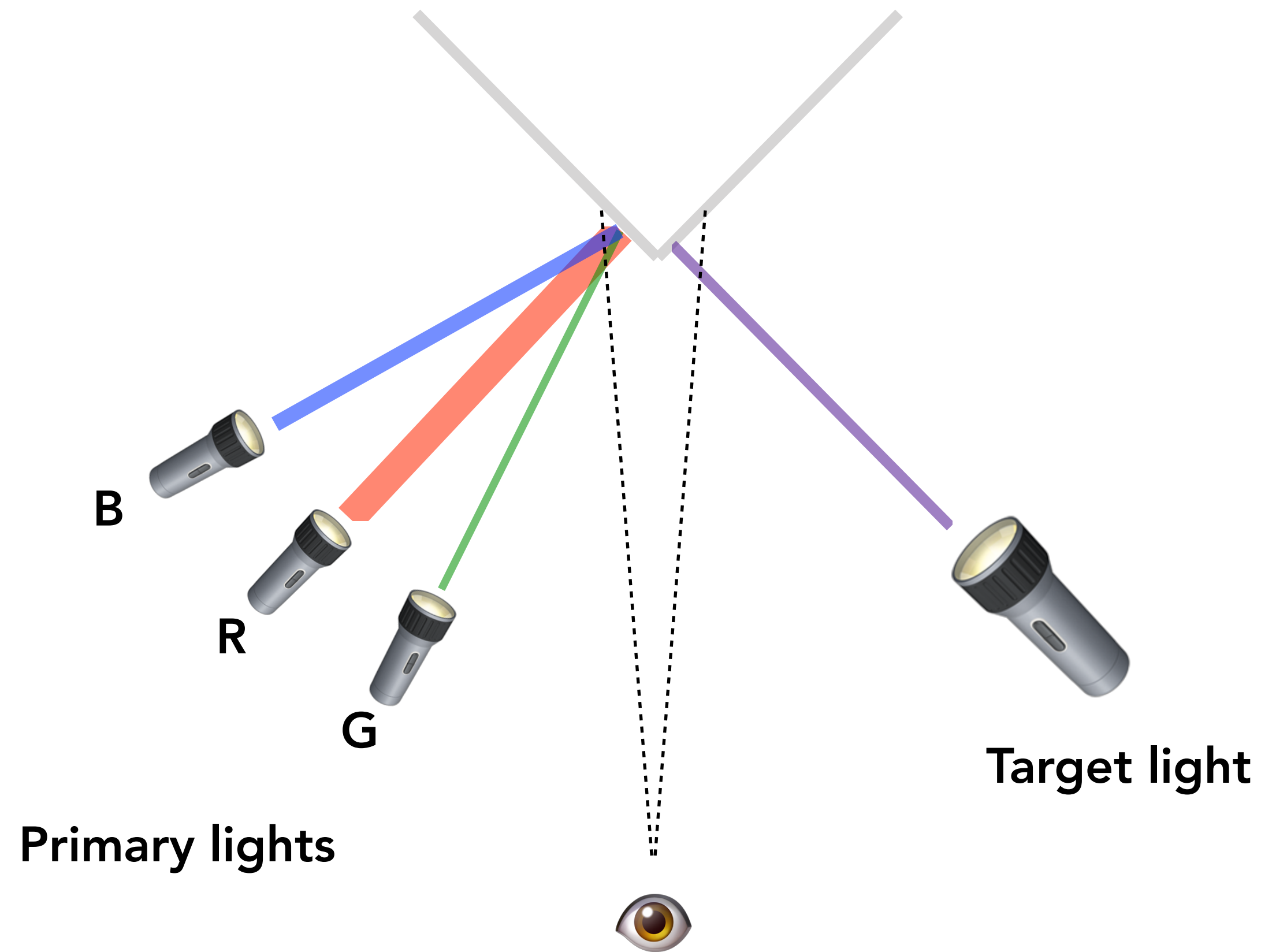
- Equivalent to solving the system of linear equations with 3 equations and 3 variables (r , g , b). The system has a unique solution (generally).

$$\begin{bmatrix} \sum R(\lambda)L(\lambda) & \sum G(\lambda)L(\lambda) & \sum B(\lambda)L(\lambda) \\ \sum R(\lambda)M(\lambda) & \sum G(\lambda)M(\lambda) & \sum B(\lambda)M(\lambda) \\ \sum R(\lambda)S(\lambda) & \sum G(\lambda)S(\lambda) & \sum B(\lambda)S(\lambda) \end{bmatrix} \times \begin{bmatrix} r \\ g \\ b \end{bmatrix} = \begin{bmatrix} \sum \Phi(\lambda)L(\lambda) \\ \sum \Phi(\lambda)M(\lambda) \\ \sum \Phi(\lambda)S(\lambda) \end{bmatrix}$$

Why Three Primary Colors?

- If only two primary colors, the system of equations has **two** variables with **three** equations, which generally doesn't have a solution, i.e., no way of finding a match, generally. Over-determined system.
- More than three primaries: more variables than equations, so there are infinitely many ways of combining the primary lights to match the target color. Under-determined system.

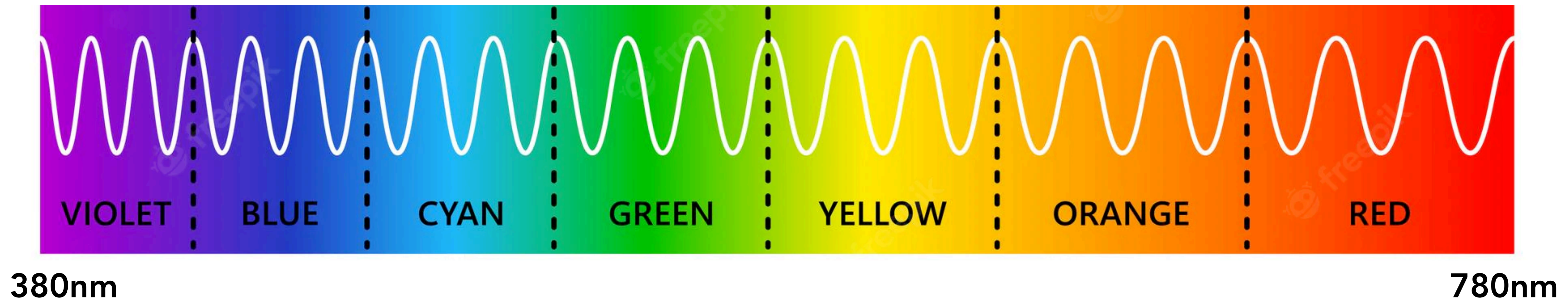
Trichromatic Theory of Color



- Conjectured by Thomas Young as early as 1801, and expanded by Helmholtz and Maxwell in 1860.
- Color matching experiments empirically verified it.
- Experimental measurement of cone sensitivities much later.
- **Pervasive applications:**
 - Color reproduction chain: display, print
 - Capture color: camera

A Note on "RGB"

- There is no one single definition of "red", "green", and "blue".
- Usually "RGB" is just synonyms for "primary lights", which usually are so chosen that they *look* red, green, and blue.
- Primary lights **don't** have to be monochromatic spectral lights.



"Amount of Primaries"

- Imagine two color spaces that use the same primary lights, but
 - one where 1 unit of R means 1 W of red light
 - the other where 1 unit of R means 10 W of red light
 - The RGB value of a given light in these two spaces will be different
- A color space must define what "one unit" of each primary light is.
- In CIE 1931 RGB color space, the "unit system" is that 1 unit of R, G, and B provides the same color as a special light called "Equal-Energy White", which has the same power over all wavelengths.
 - If you are building your own color space, you can choose whatever "white" you want.

A RGB Color Space

- Given the exact spectra of the “RGB” primary lights $R(\lambda)$, $G(\lambda)$, and $B(\lambda)$, we have a color space.
 - What this means is that the color of any arbitrary light $\Phi(\lambda)$ can be expressed as a point in that 3D coordinate system.
- That is, we can mathematically study colors now — colorimetry.

$$\begin{bmatrix} \sum R(\lambda)L(\lambda) & \sum G(\lambda)L(\lambda) & \sum B(\lambda)L(\lambda) \\ \sum R(\lambda)M(\lambda) & \sum G(\lambda)M(\lambda) & \sum B(\lambda)M(\lambda) \\ \sum R(\lambda)S(\lambda) & \sum G(\lambda)S(\lambda) & \sum B(\lambda)S(\lambda) \end{bmatrix} \times \begin{bmatrix} r \\ g \\ b \end{bmatrix} = \begin{bmatrix} \sum \Phi(\lambda)L(\lambda) \\ \sum \Phi(\lambda)M(\lambda) \\ \sum \Phi(\lambda)S(\lambda) \end{bmatrix}$$

Geometric Transformation Perspective

- So far we've seen two ways to express a color in a 3D space:
 - A color can be expressed as its three cone responses (l, m, s)
 - A color can also be expressed as the amount of primary lights (r, g, b) needed
- How are the two expressions related?

$$\begin{bmatrix} \sum \Phi(\lambda)L(\lambda) \\ \sum \Phi(\lambda)M(\lambda) \\ \sum \Phi(\lambda)S(\lambda) \end{bmatrix} = \begin{bmatrix} l \\ m \\ s \end{bmatrix}$$

Geometric Transformation Perspective

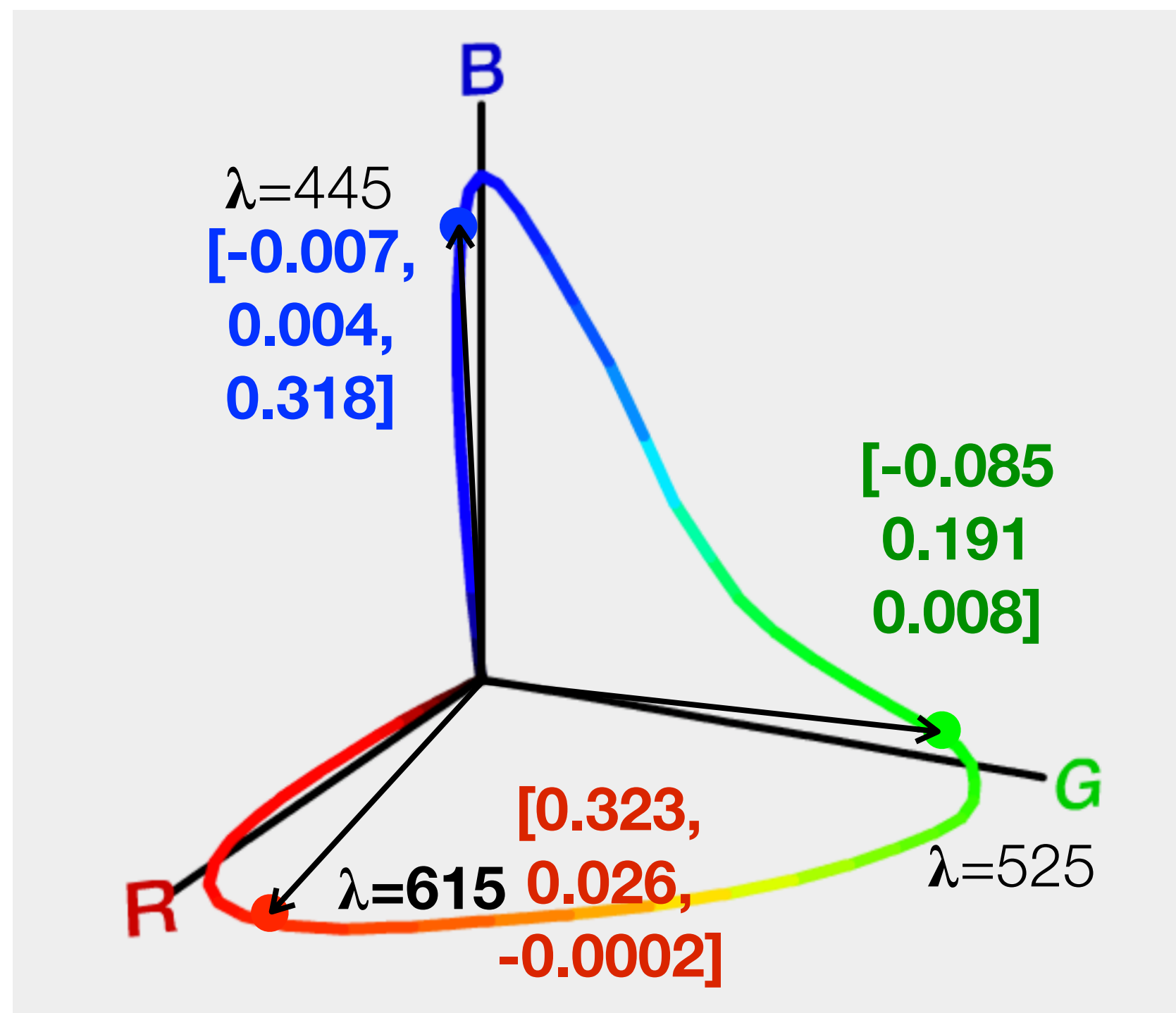
- Expressing a color from the $[l, m, s]$ coordinates to the $[r, g, b]$ coordinates is a geometric transformation.
- Equivalently, it's a transformation of the coordinate systems (color spaces)!
 - Because the transformation matrix is constant, metamers in RGB space are metamers in LMS space too.

Transformation matrix from the RGB space to the LMS space

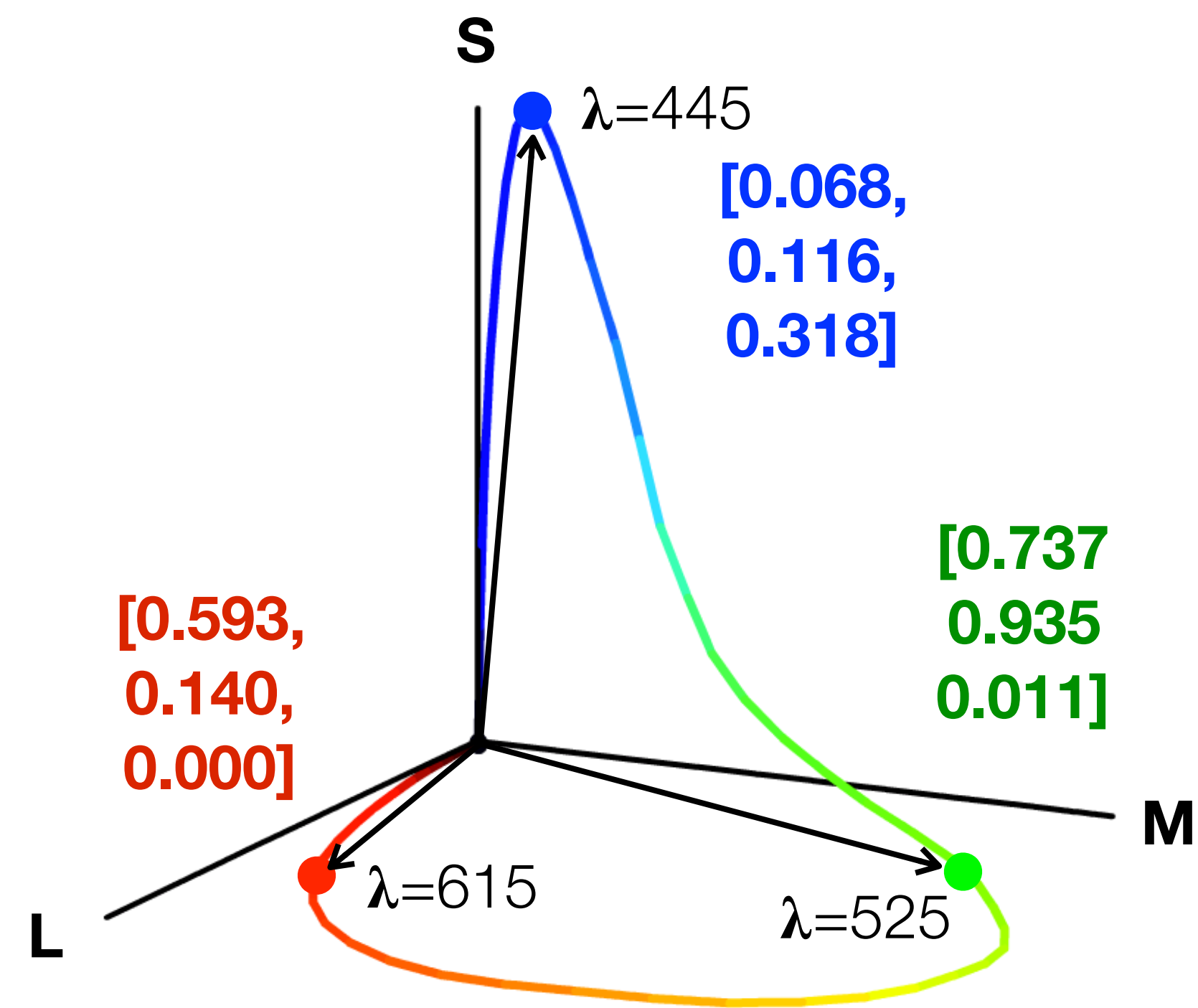
$$\begin{bmatrix} \sum R(\lambda)L(\lambda) & \sum G(\lambda)L(\lambda) & \sum B(\lambda)L(\lambda) \\ \sum R(\lambda)M(\lambda) & \sum G(\lambda)M(\lambda) & \sum B(\lambda)M(\lambda) \\ \sum R(\lambda)S(\lambda) & \sum G(\lambda)S(\lambda) & \sum B(\lambda)S(\lambda) \end{bmatrix} \times \begin{bmatrix} r \\ g \\ b \end{bmatrix} = \begin{bmatrix} \sum \Phi(\lambda)L(\lambda) \\ \sum \Phi(\lambda)M(\lambda) \\ \sum \Phi(\lambda)S(\lambda) \end{bmatrix} = \begin{bmatrix} l \\ m \\ s \end{bmatrix}$$

CIE 1931 RGB \leftrightarrow LMS Spaces

Spectral lights in the CIE 1931 RGB space



Spectral lights in the LMS space



Post-Receptoral Color Encoding

- Behavioral Intuition
- Hue Cancellation
- Neural & Physiological Basis

Subjective Descriptions of Color



Subjective Descriptions of Color



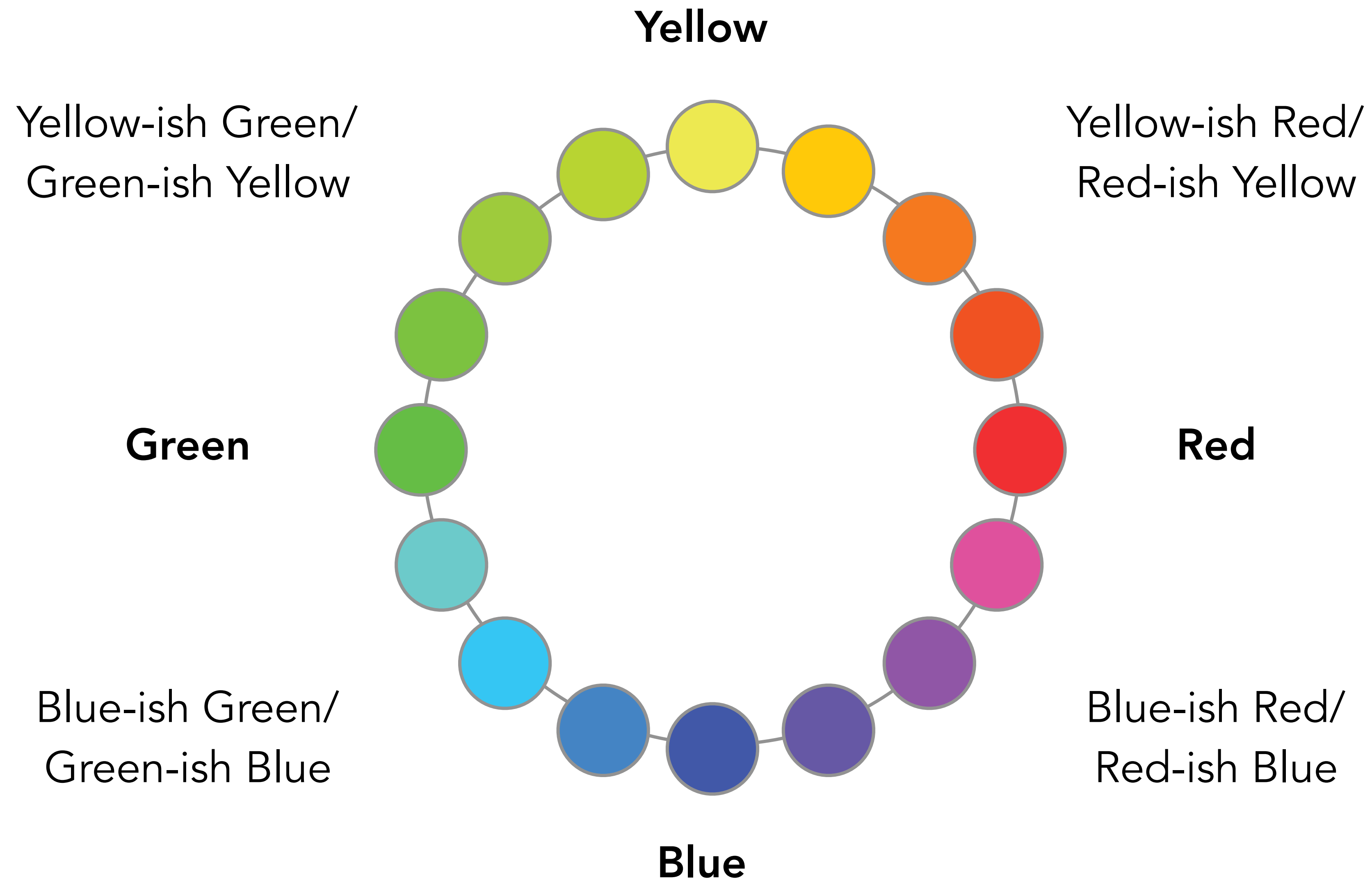
Subjective Descriptions of Color



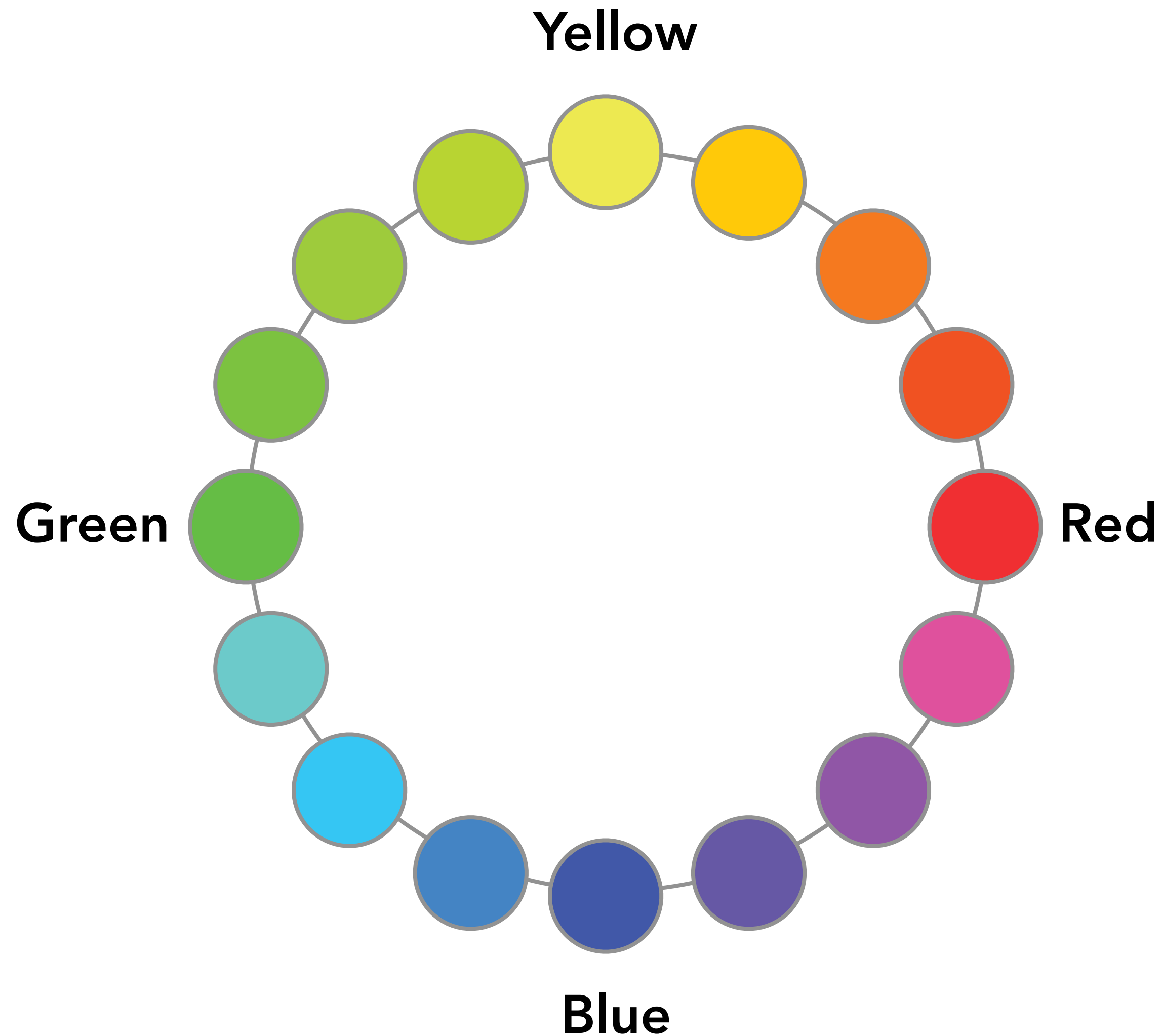
Subjective Descriptions of Color



Subjective Descriptions of Color

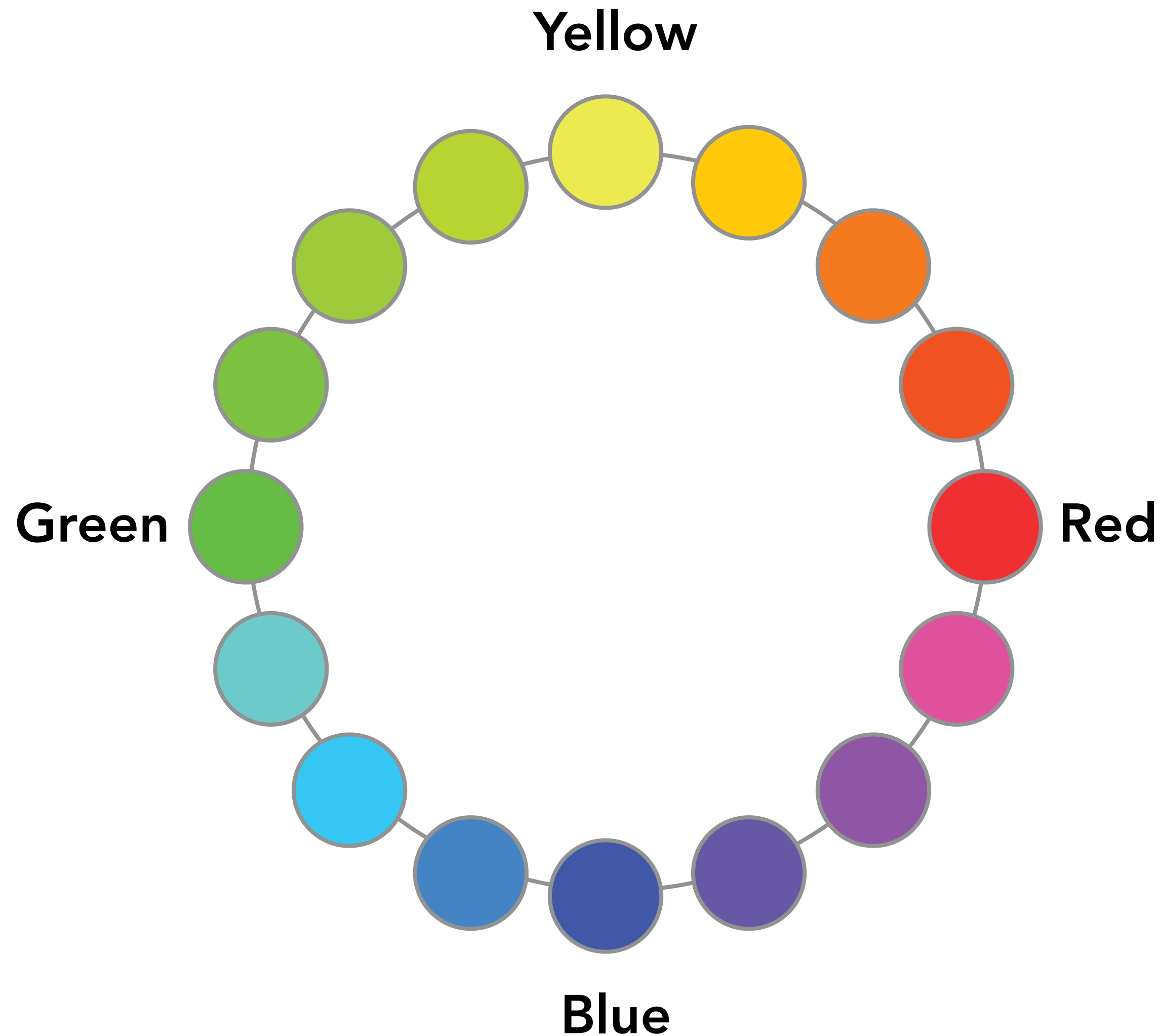


Red-ish Green?



- Physically if you mix red lights with green lights you get **yellow**, but if you stare at a **yellow** color, would you say it has any red or any green? Perhaps not.
- You also wouldn't say **blue** has any contribution from red or green.
- Perceptually, it seems like red and green can never co-exist in a color.

Yellow-ish Blue?

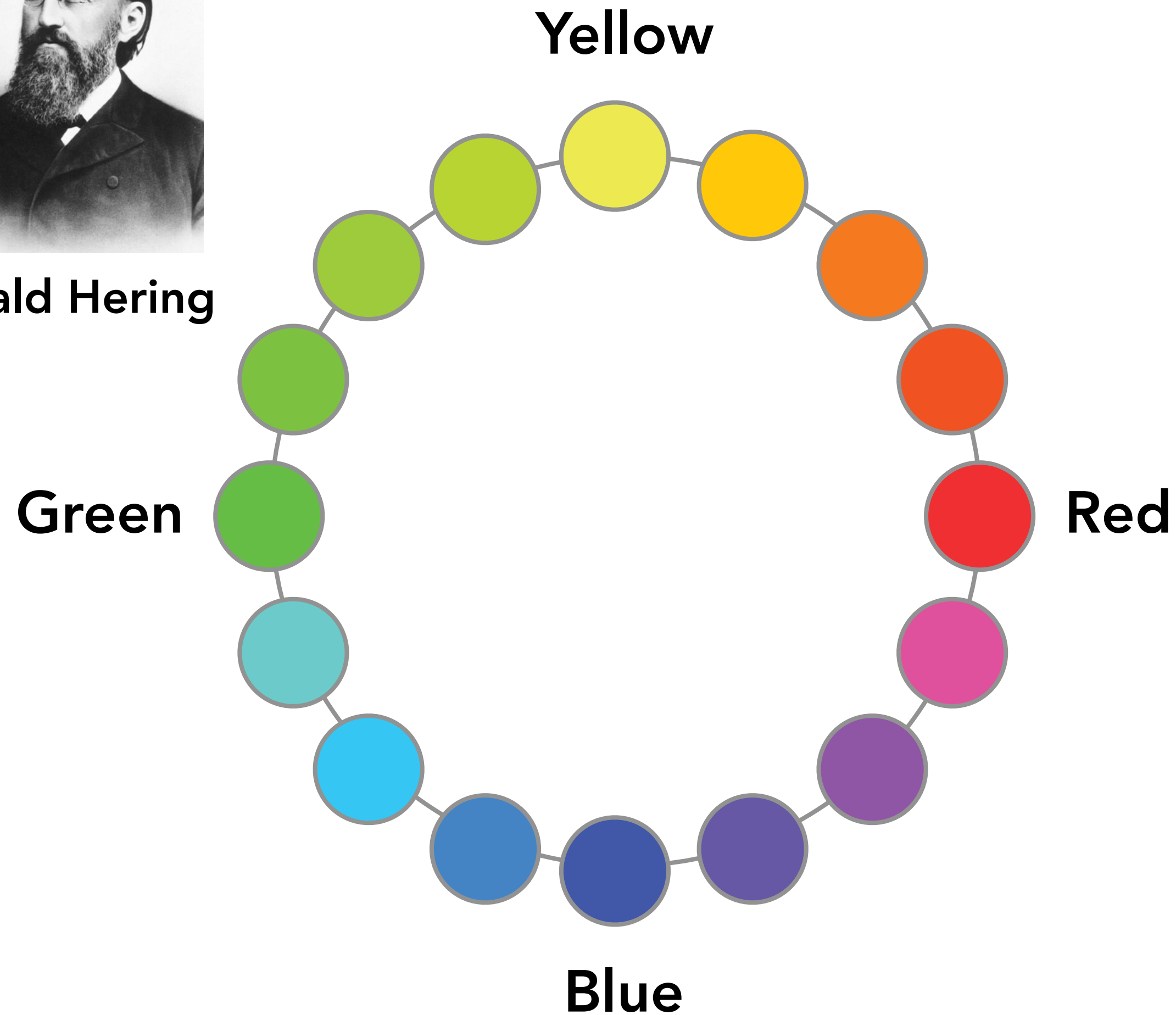


- **Perceptually:**
 - You wouldn't say green has any blue or any yellow.
 - You wouldn't say red has any blue or any yellow.
- **Perceptually, it seems like yellow and blue can never co-exist in a color.**

Perceptual Color Organization



Ewald Hering

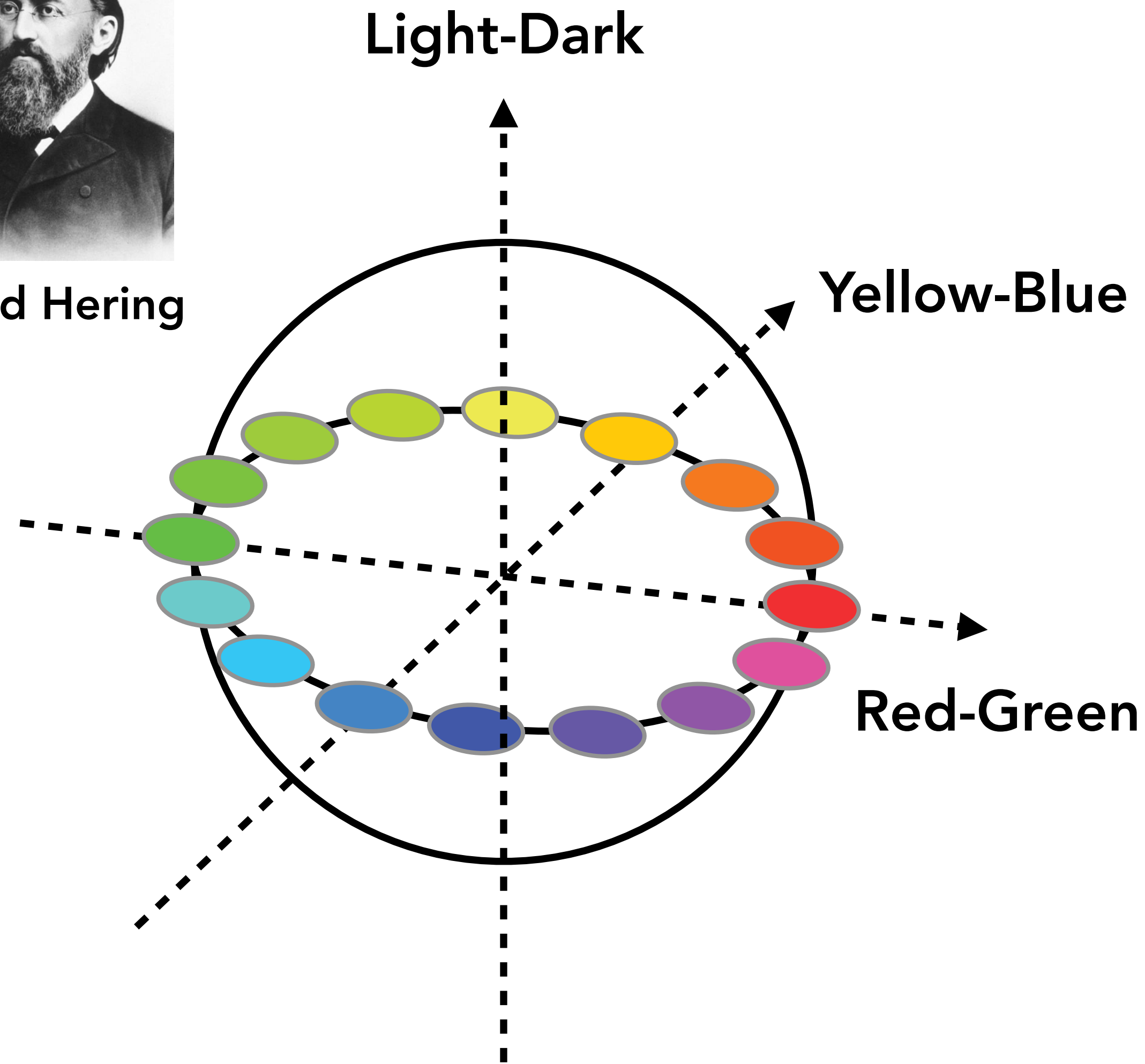


- Perceptually, there are four unique hues: Yellow, Blue, Red, Green.
- Y-B are opposing hues and R-G are opposing hues.
- No unique hue can be described as a combination of other unique hues.
- This is **perceptually** rather than **physical**: you can get yellow by mixing green with red physically, but if you just stares at yellow, they perceptually don't see a yellow color as having red or green contribution.

Perceptual Color Organization



Ewald Hering



- There is also a light-dark opponent process.
- Any color can be described as a combination of three non-opposing dimensions:
 - E.g., some amount of yellow + red + light

Post-Receptoral Color Encoding

- Behavioral Intuition
- Hue Cancellation
- Neural & Physiological Basis

Hue Cancellation Experiment

JOURNAL OF THE OPTICAL SOCIETY OF AMERICA

VOLUME 45, NUMBER 7

JULY, 1955

Some Quantitative Aspects of an Opponent-Colors Theory. I. Chromatic Responses and Spectral Saturation

DOROTHEA JAMESON AND LEO M. HURVICH

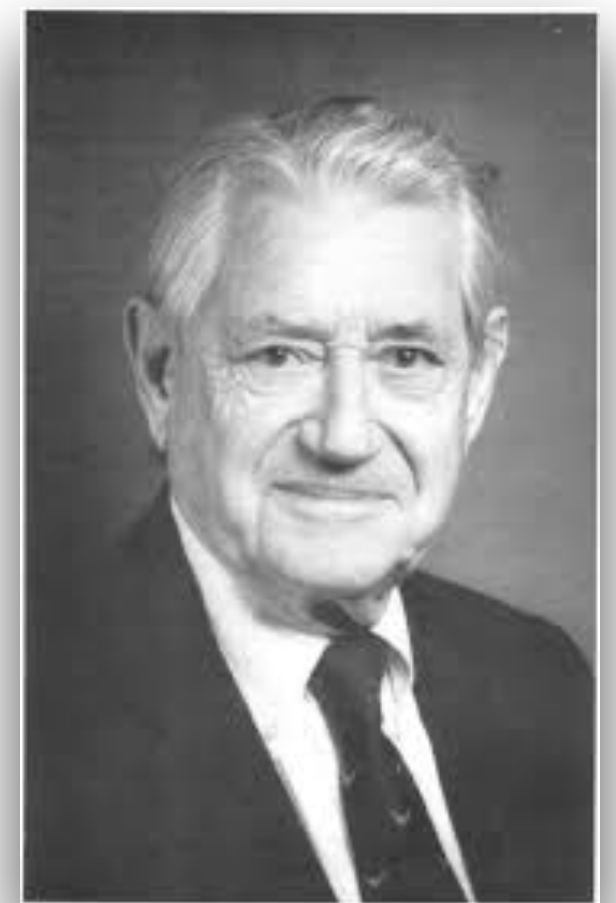
Color Technology Division, Eastman Kodak Company, Rochester, New York

(Received January 21, 1955)

Saturation discrimination is assumed to be dependent on the ratio of chromatic to achromatic components in the sensory response to a given wavelength. The usual methods of measurement do not, however, permit independent control of the chromatic and achromatic variables. On the basis of an opponent-colors theory of vision, a method is described for measuring directly and separately the spectral distributions of the chromatic components. A series of experiments is reported in which this method was used to obtain measures of the paired chromatic responses associated with the four primary spectral hues. Results are reported for two observers, 1° foveal test field, for an equal brightness spectrum (10 mL), and a neutral state of adaptation (10 mL). The measured chromatic responses, together with achromatic (luminosity) functions measured earlier for the same observers, are used to predict the form of the spectral saturation discrimination function.

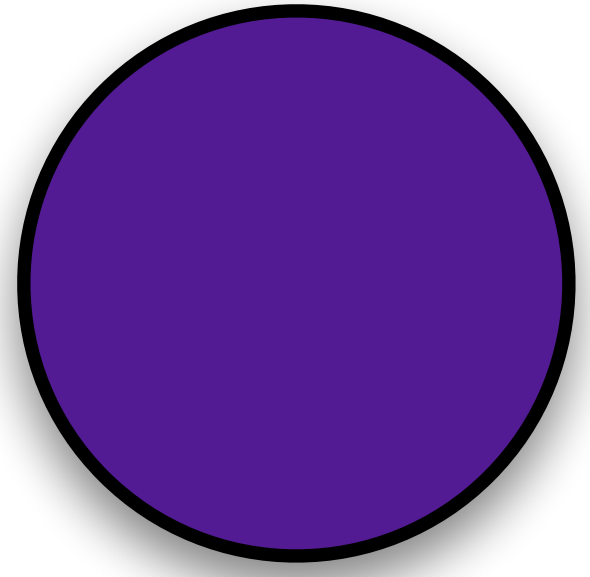
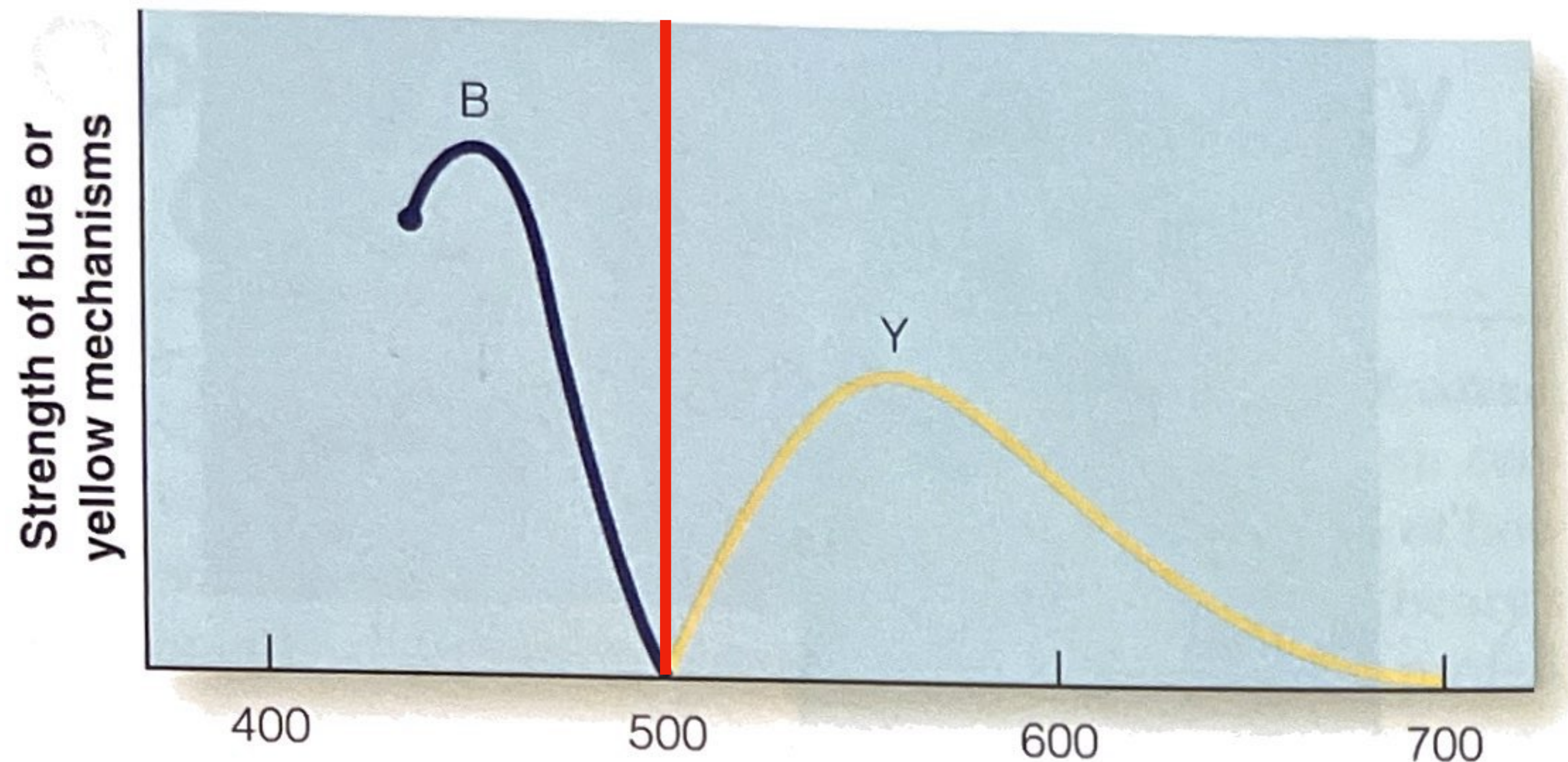


Jameson



Hurvich

Hue Cancellation Experiment: Yellow-Blue

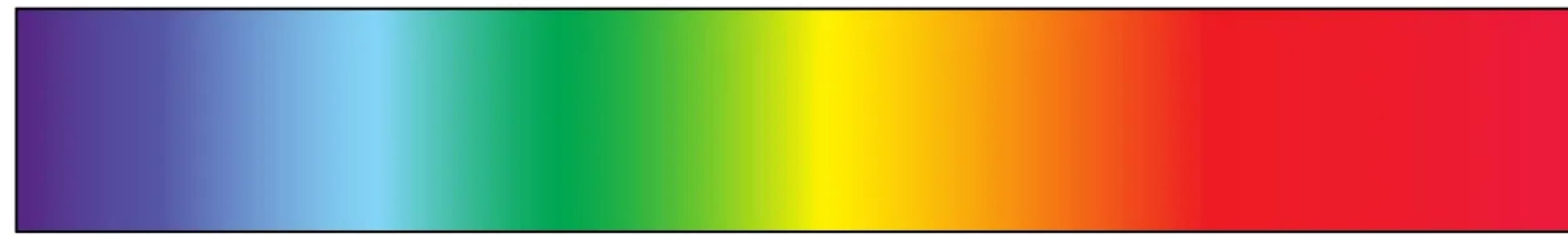


Test Light



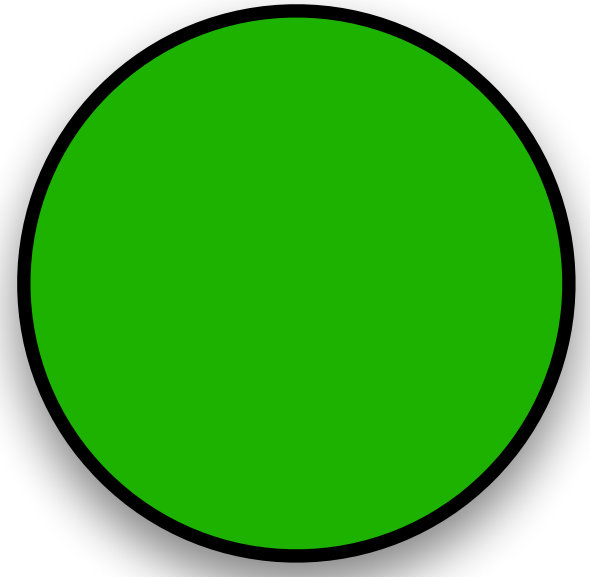
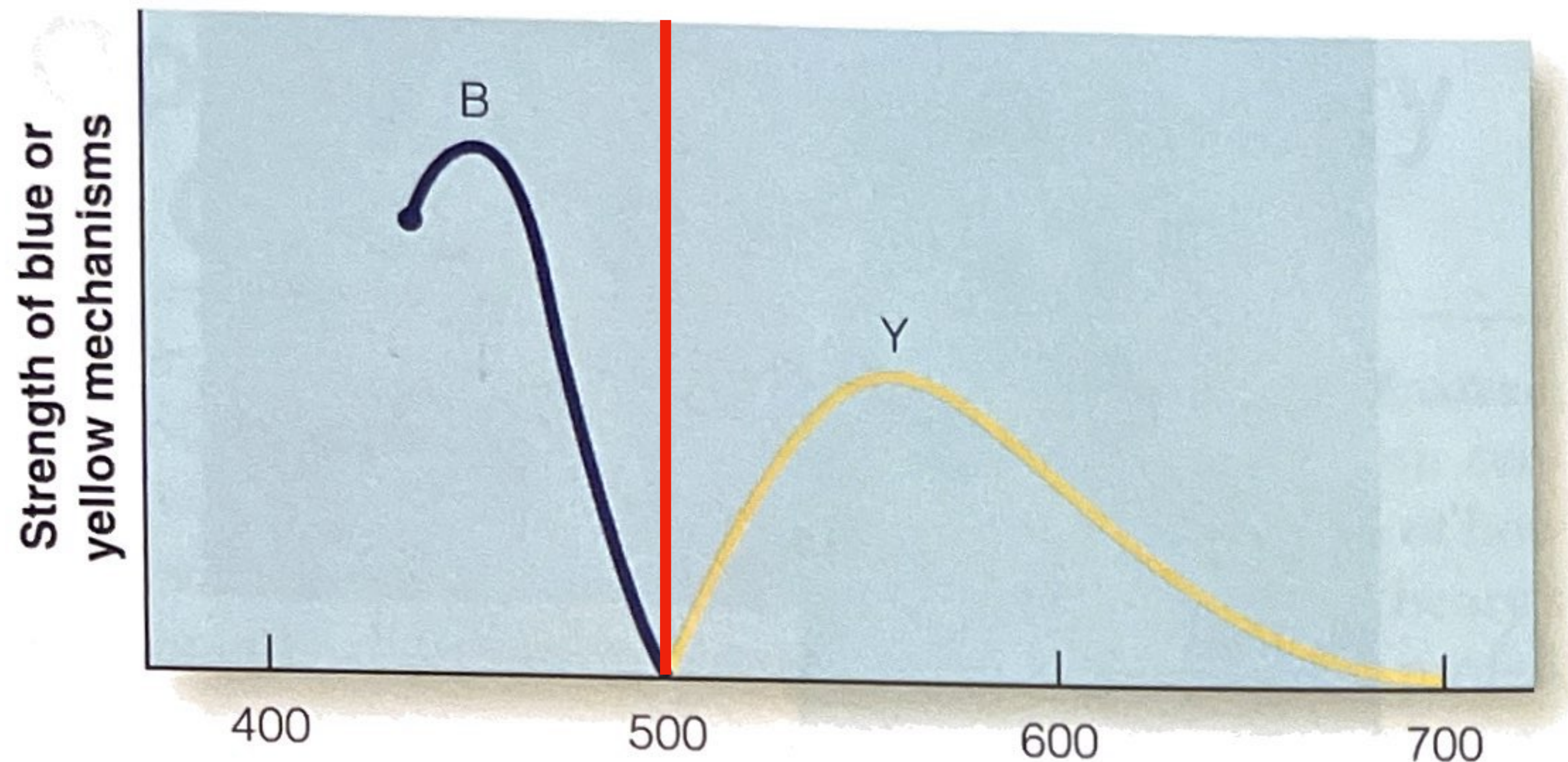
Cancellation Light

Test light wavelength



Goal: adjust the power of the cancellation light so that the **mixture** of test and cancellation lights looks **neither blue nor yellow**

Hue Cancellation Experiment: Yellow-Blue

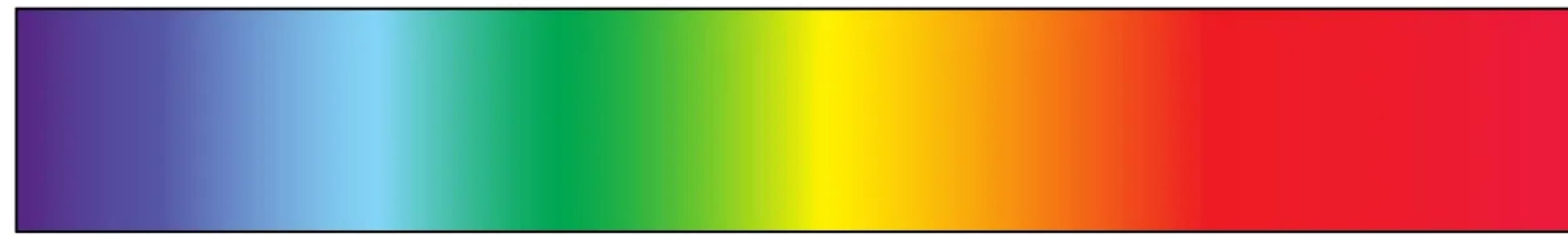


Test Light



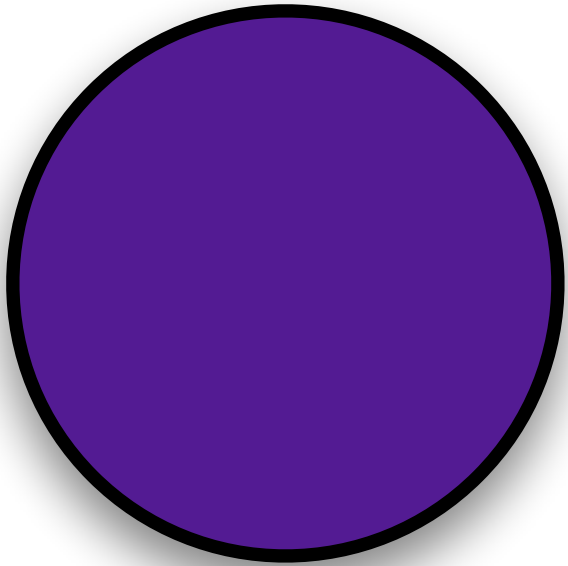
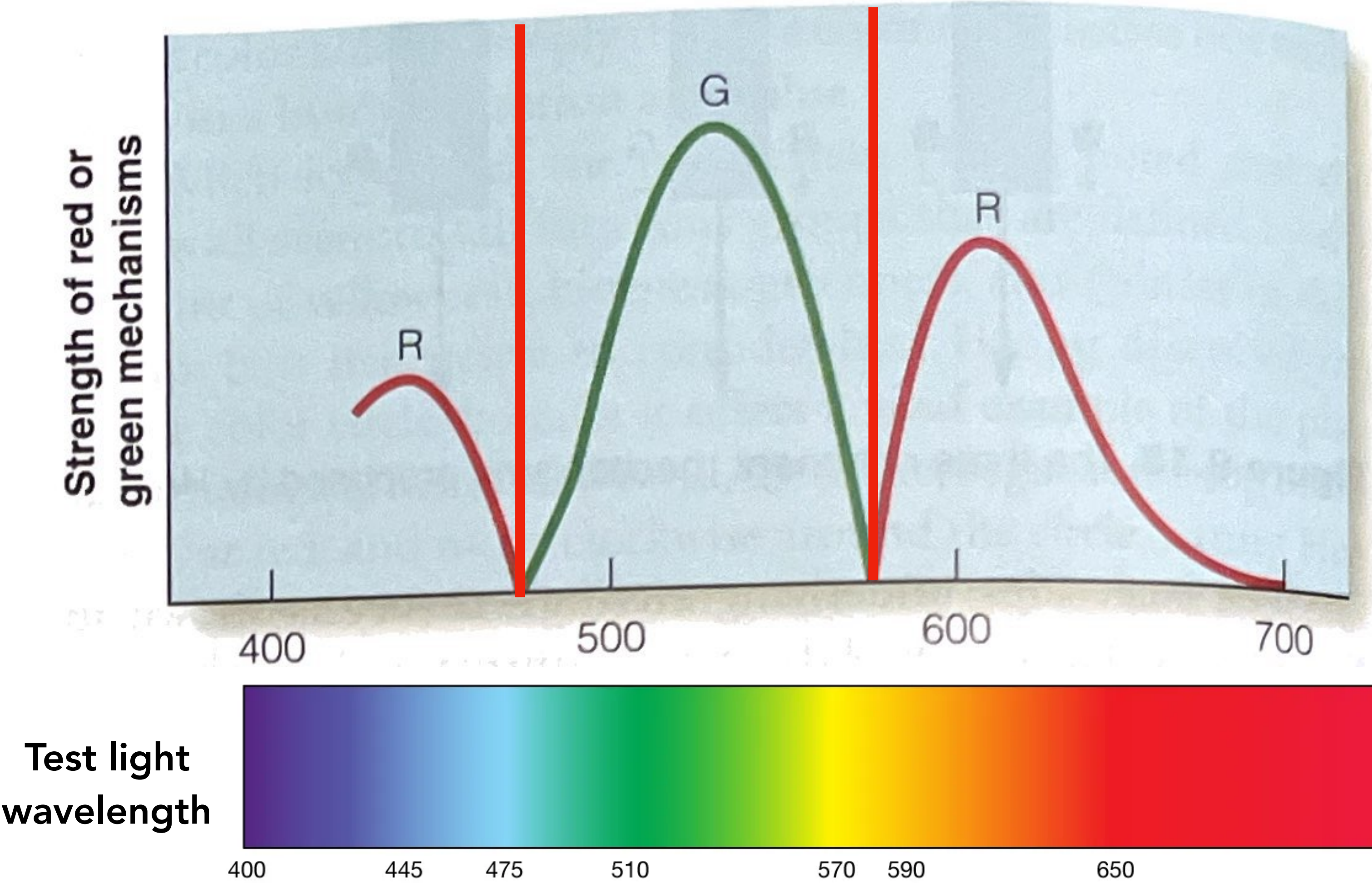
Cancellation Light

Test light wavelength



Goal: adjust the power of the cancellation light so that the **mixture** of test and cancellation lights looks **neither blue nor yellow**

Hue Cancellation Experiment: Red-Green



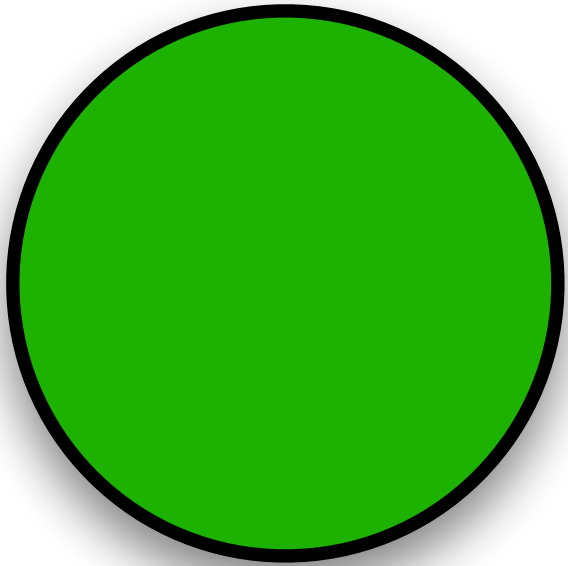
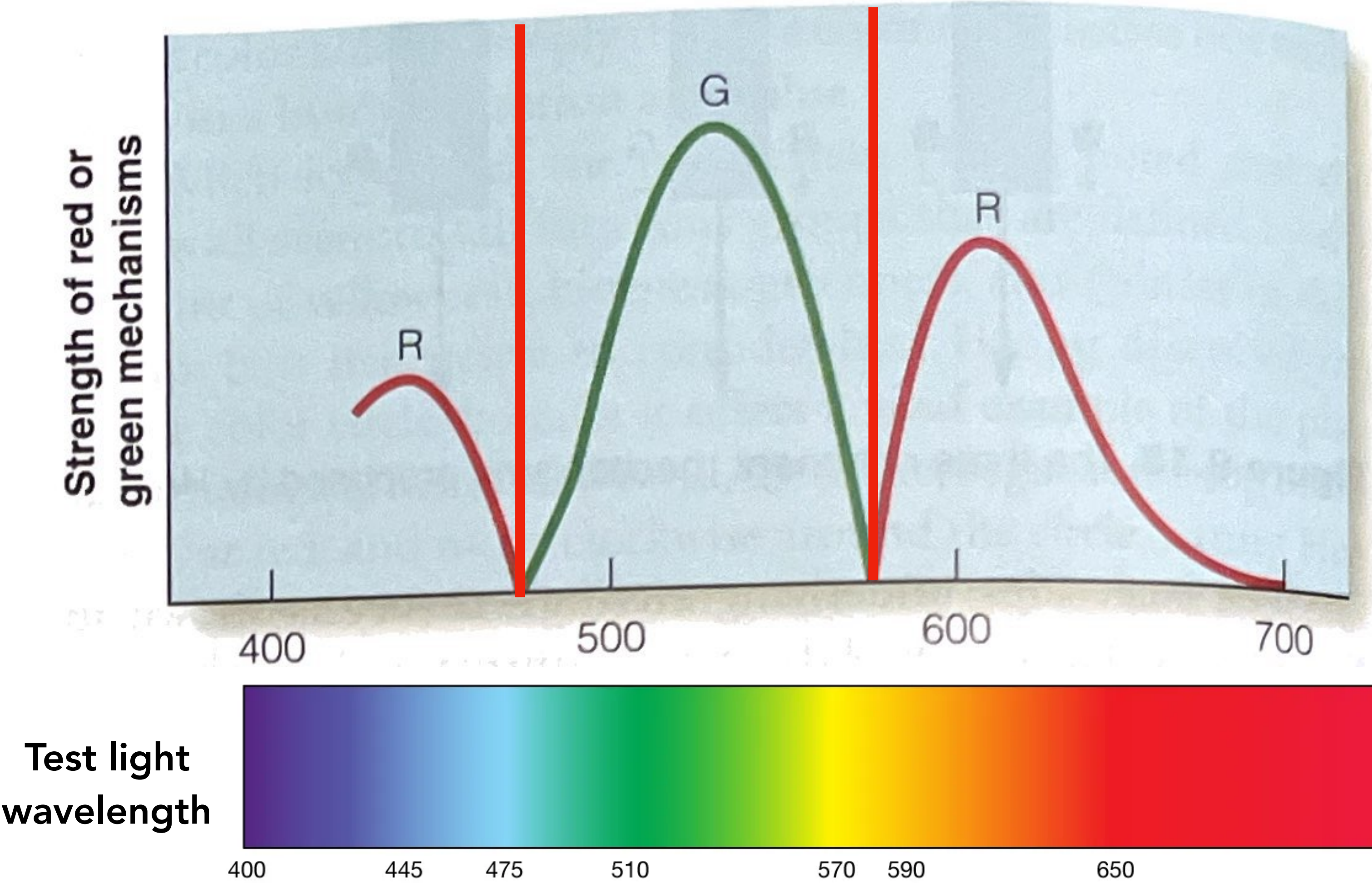
Test Light



Cancellation Light

Goal: adjust the power of the cancellation light so that the **mixture** of test and cancellation lights looks **neither red nor green**

Hue Cancellation Experiment: Red-Green



Test Light



Cancellation Light

Goal: adjust the power of the cancellation light so that the **mixture** of test and cancellation lights looks **neither red nor green**

Overall Results

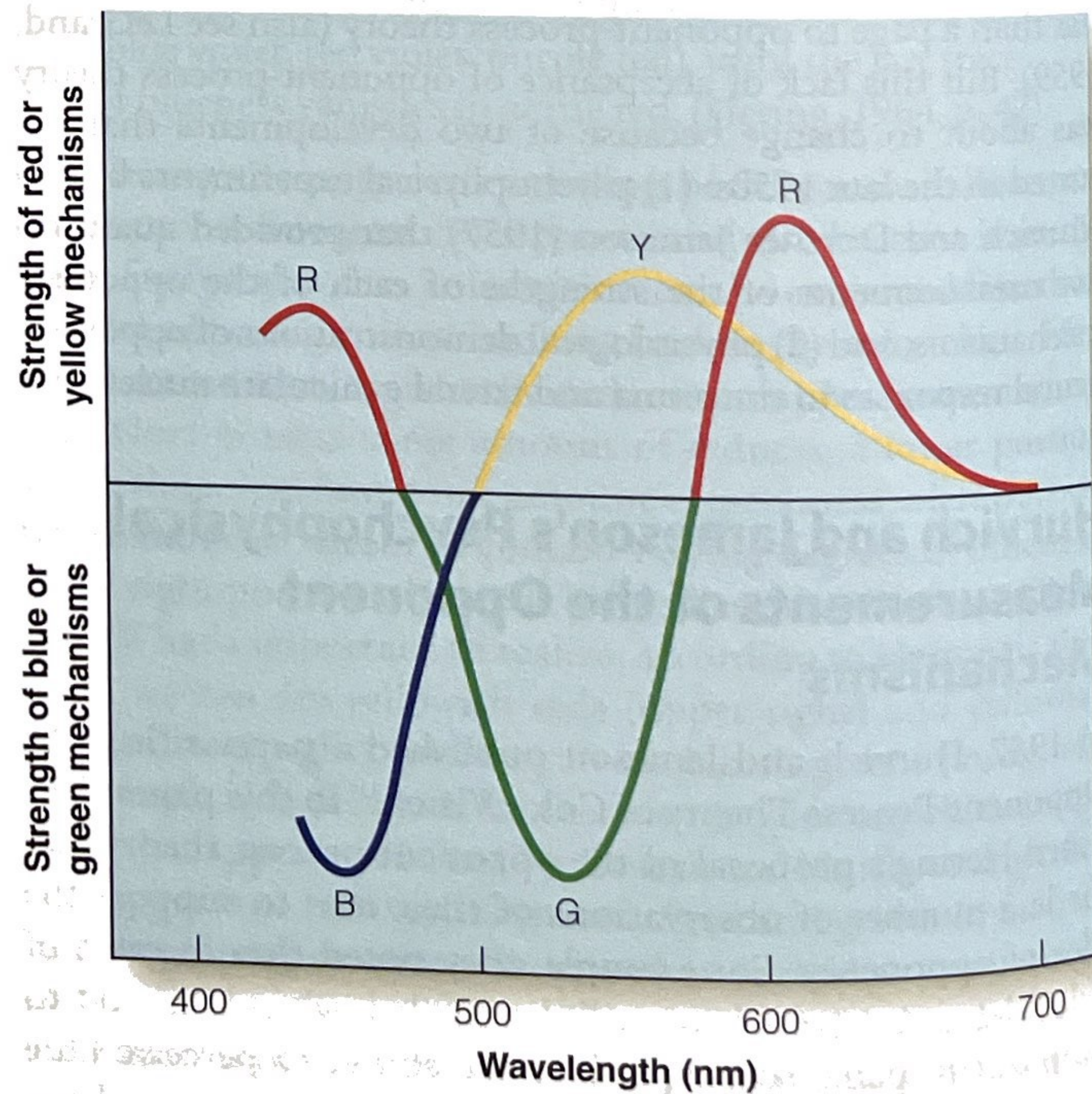
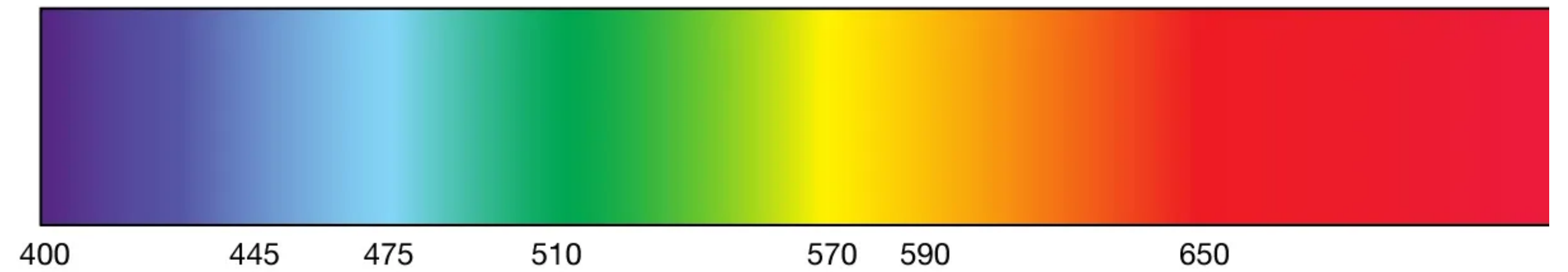
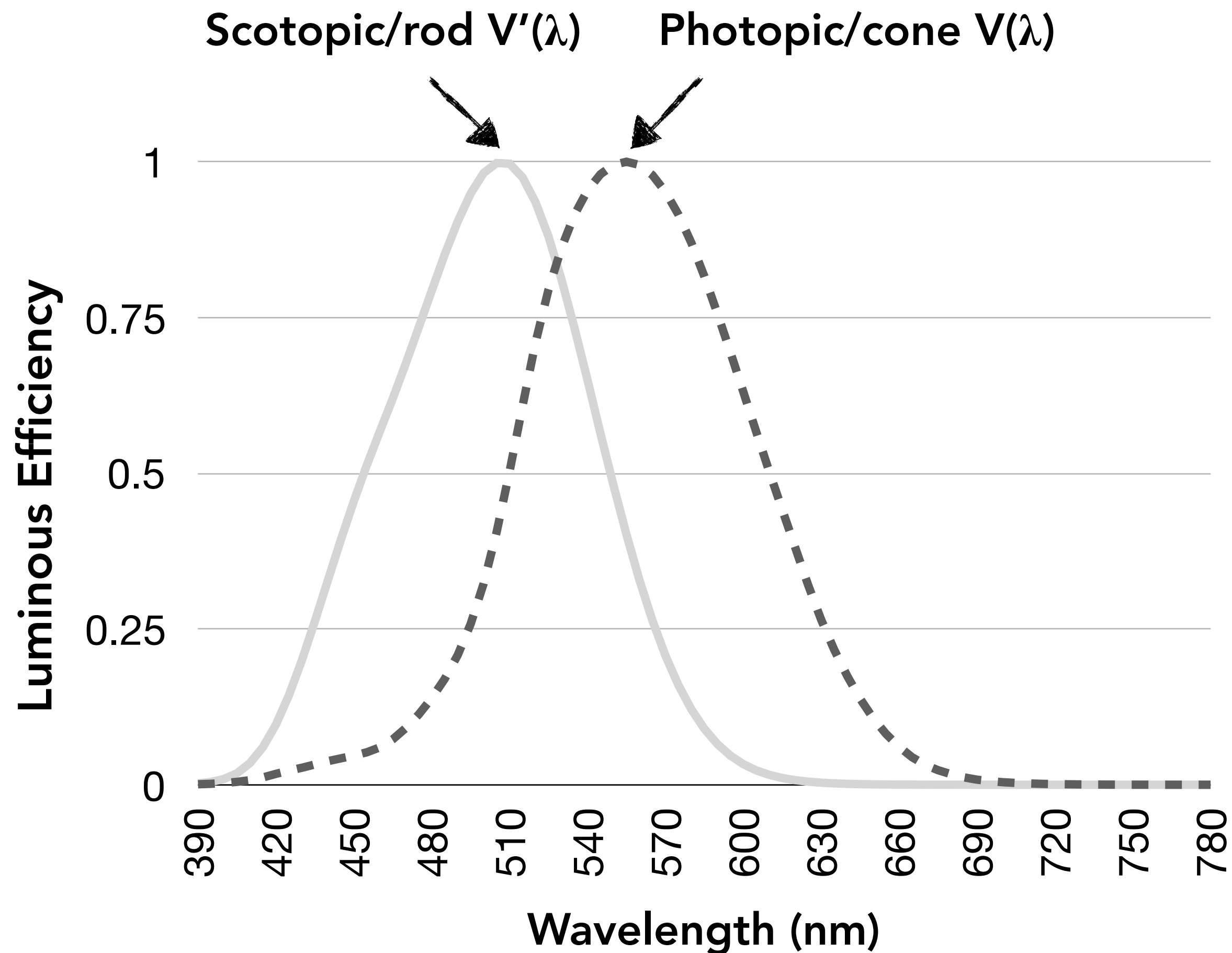


Figure 9.22 The curves of Figures 9.20 and 9.21 plotted together, with the blue and green curves inverted to indicate the opponent nature of the blue–yellow and red–green pairs. (From Hurvich & Jameson, 1957)



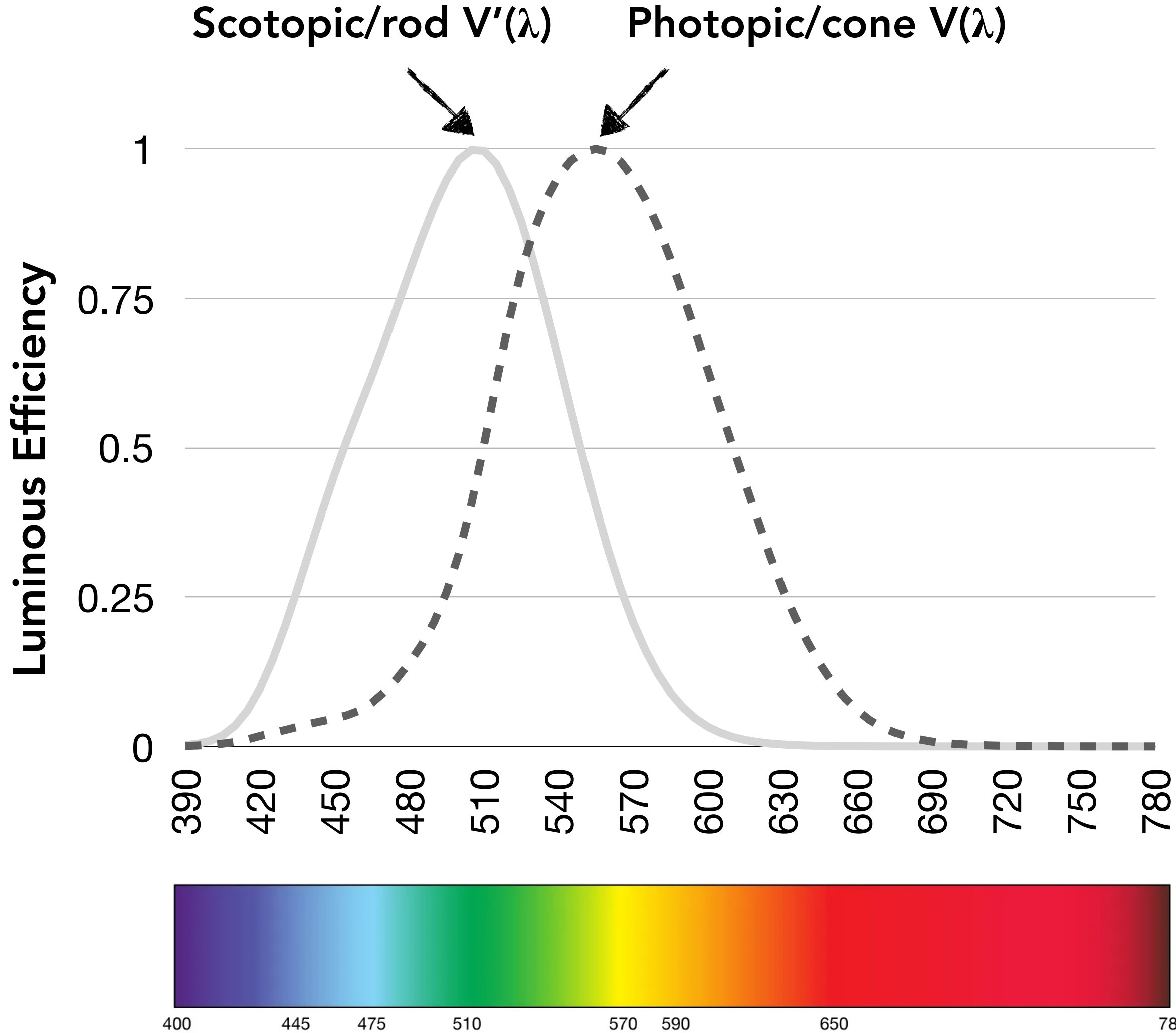
- Take the color appearance here with a huge grain of salt, since neither paper, your laptop, nor the classroom project can accurately reproduce the colors of single-wavelength, spectral lights.

Light-Darkness: Luminous Efficiency Function



- Efficiency is inversely proportional to how much power you need at each wavelength to reach a criterion level of brightness
- Use Heterochromatic Flicker Photometry (HPE).
 - Alternate between a test light and a reference light at say, 25 Hz
 - Adjust the power of the test light so that there is no flickering

Purkinje Shift



Red looks brighter in daylight



Green looks brighter at dawn

Post-Receptoral Color Encoding

- Behavioral Intuition
- Hue Cancellation
- Neural & Physiological Basis

Does Opponent Theory Contradict Trichromacy?

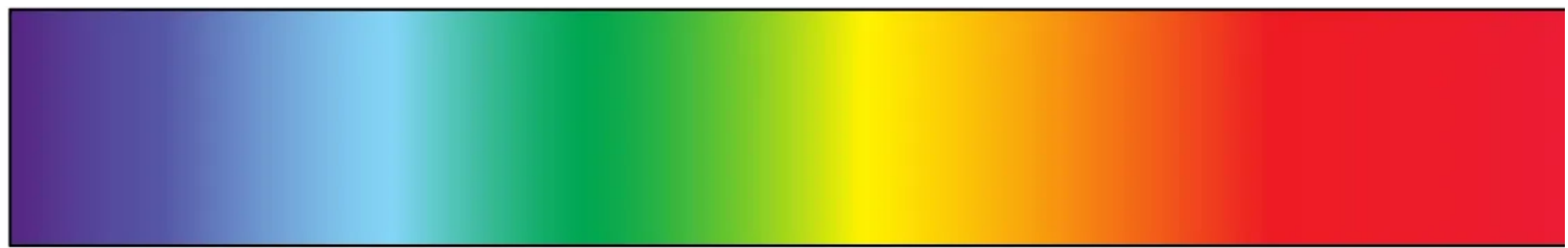
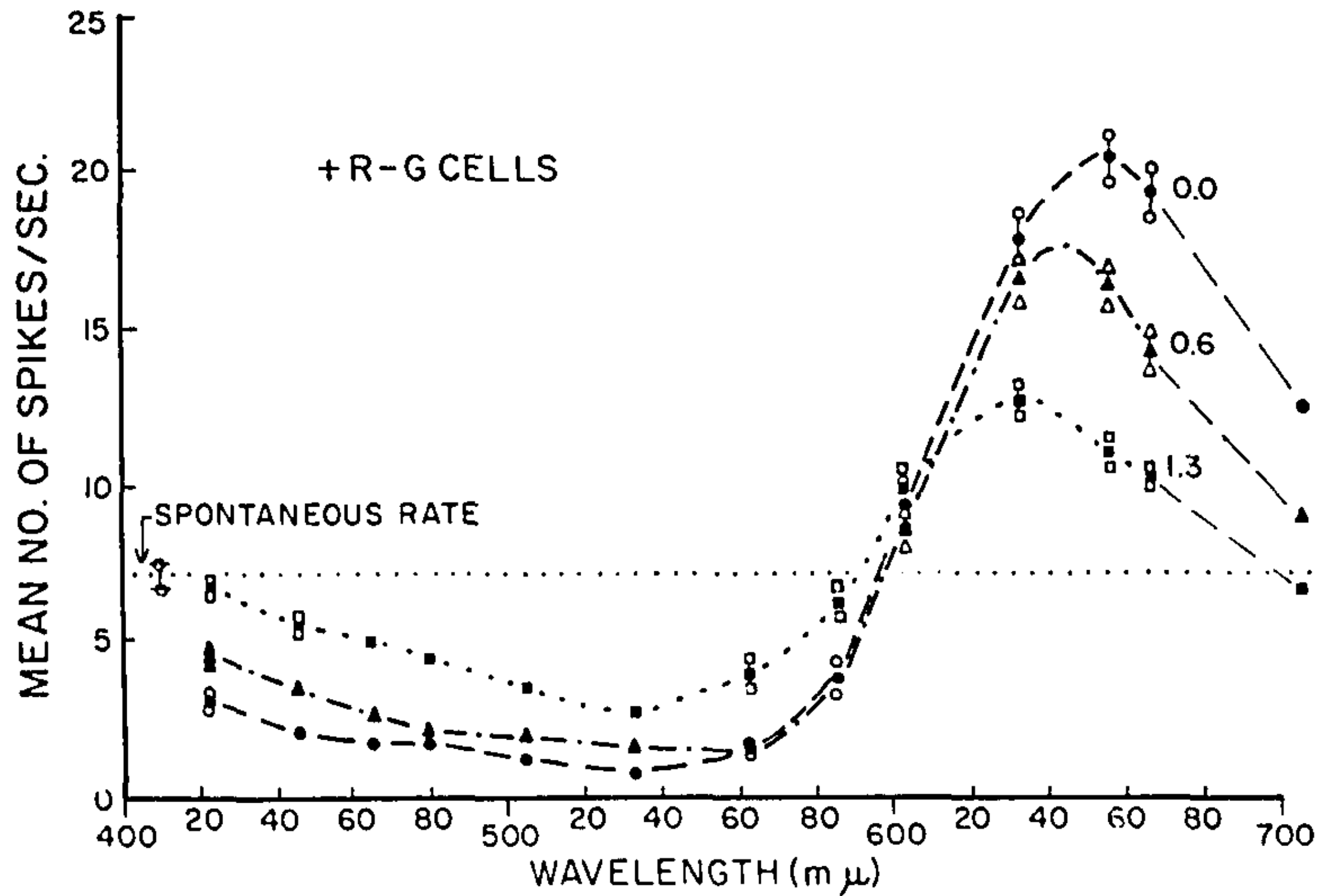
- **Trichromacy: any color can be mixed from three primary colors.**
 - We know the neural basis for this: we have three classes of cones.
 - We've seen the linear system derivation of trichromacy.
- **Opponent theory seems to contradict that:**
 - Three unique opponent processes (Y-B, R-G, White-Black)
 - Any color is constructed from a hue and a lightness (white-black)
 - Any hue can be described as a combination of two non-opposing primary hues

Does Opponent Theory Contradict Trichromacy?

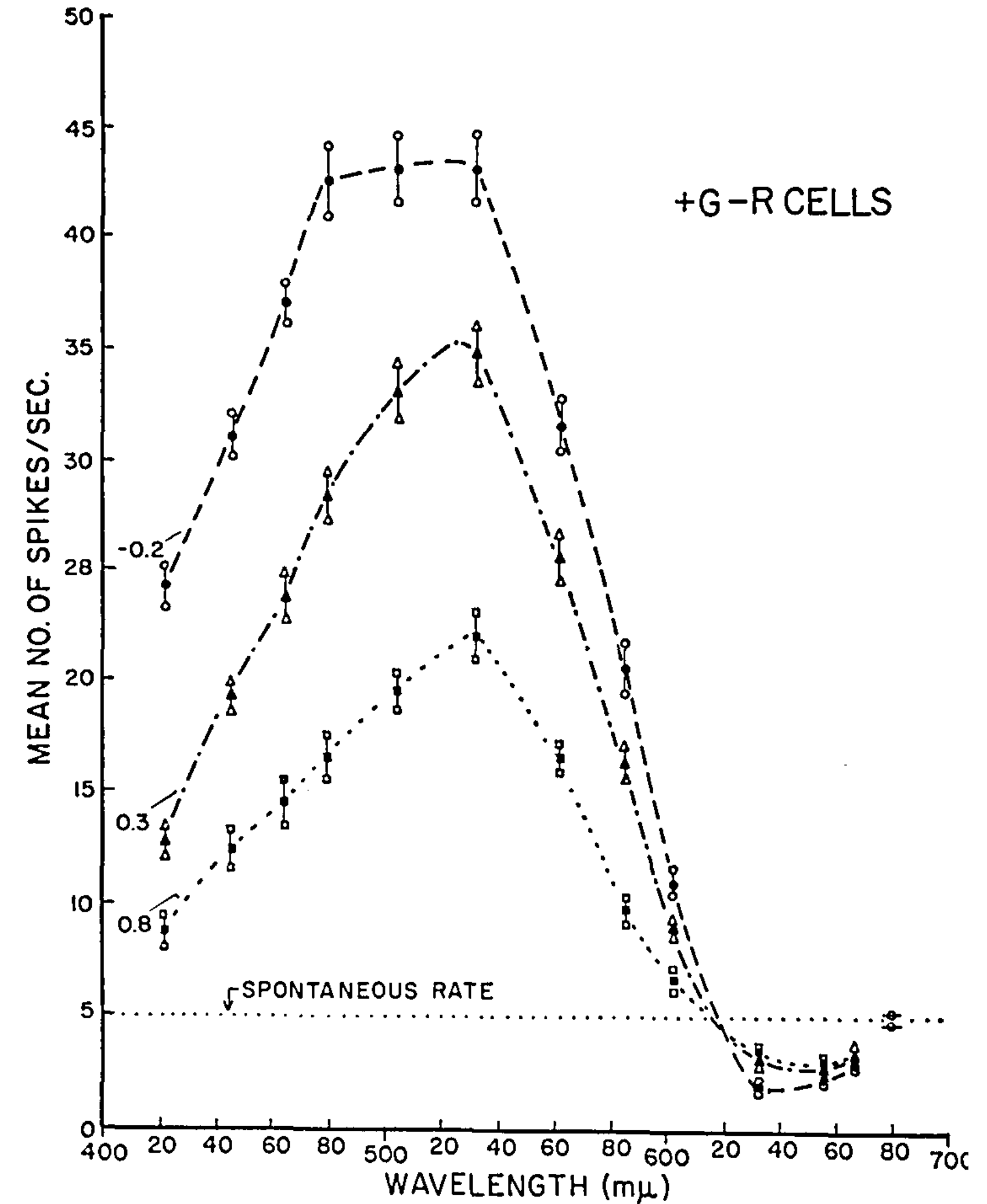
- The hue cancellation experiment quantitatively solidifies the opponent theory, but:
 - Are there any neural/physiological basis for this theory? **Yes**
 - Are they the same mechanisms behind trichromacy? **No (the fact that we have three classes of cone can't explain opponent processes, which involve new neural mechanisms)**

Spectrally-Opponent Cells in LGN (~ = RGCs)

*on macaques; different curves represent different light intensities

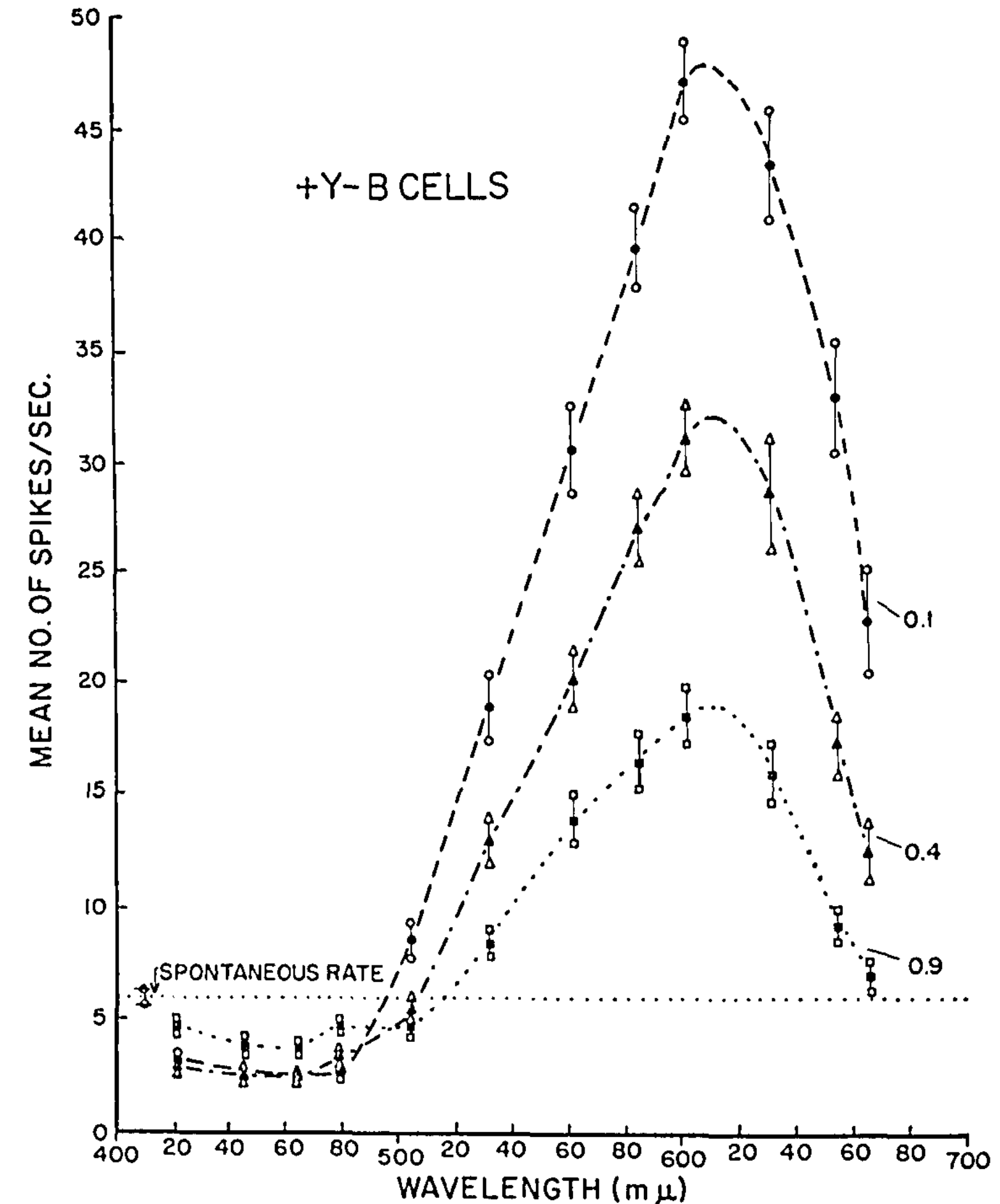
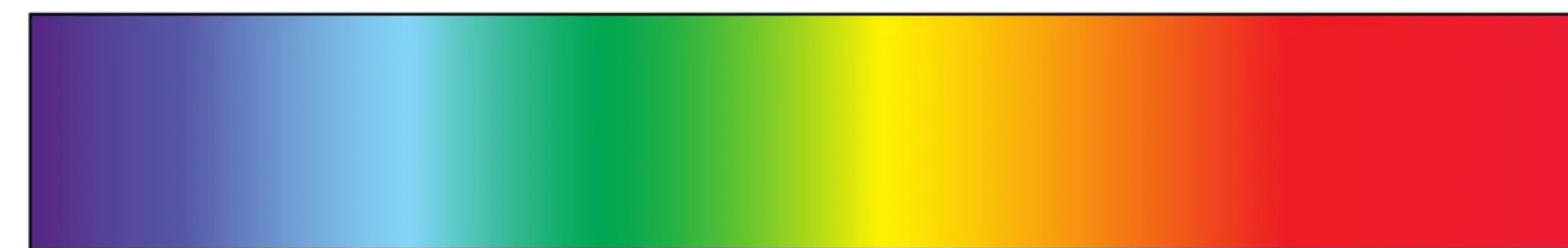
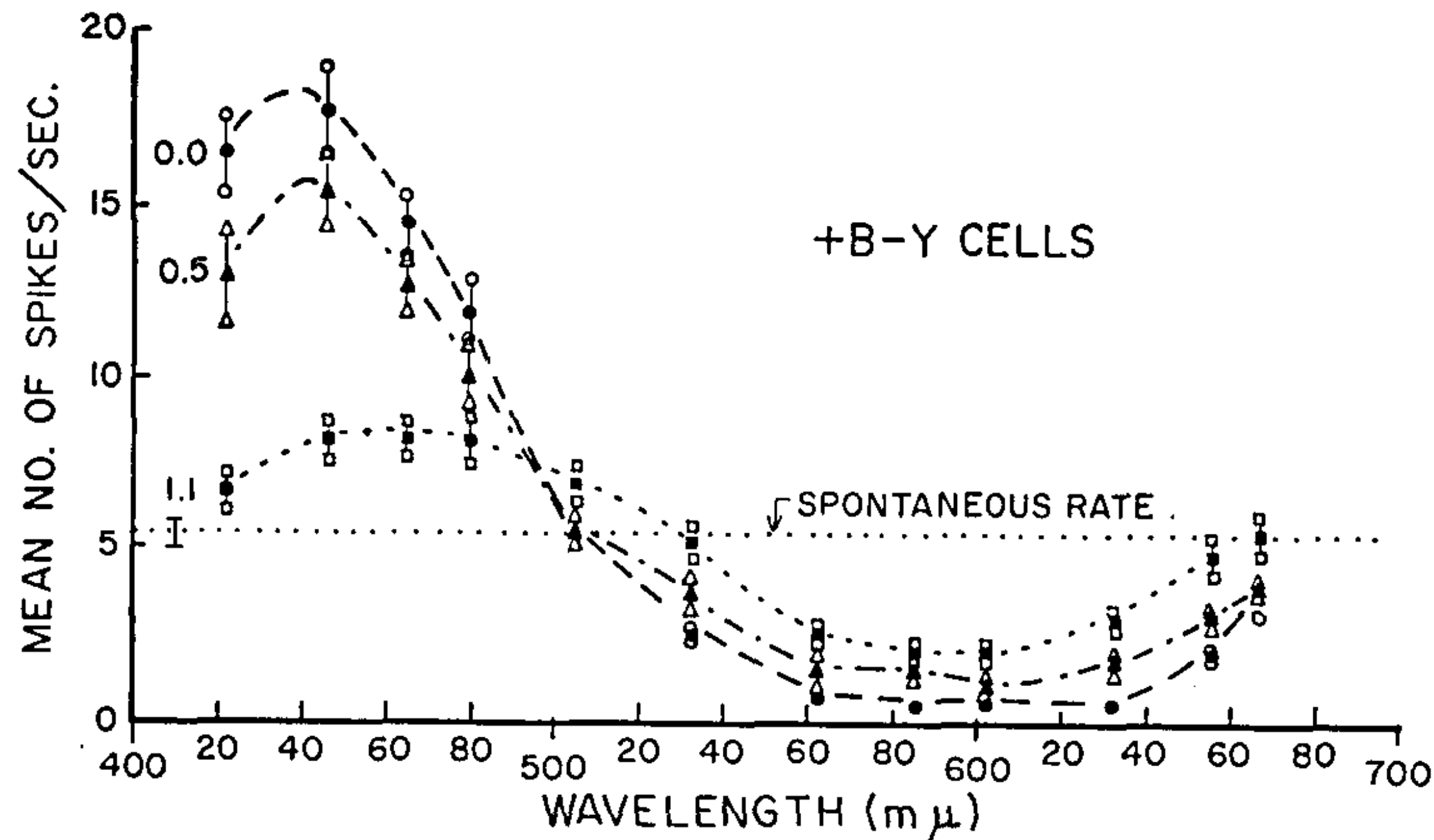


400 445 475 510 570 590 650



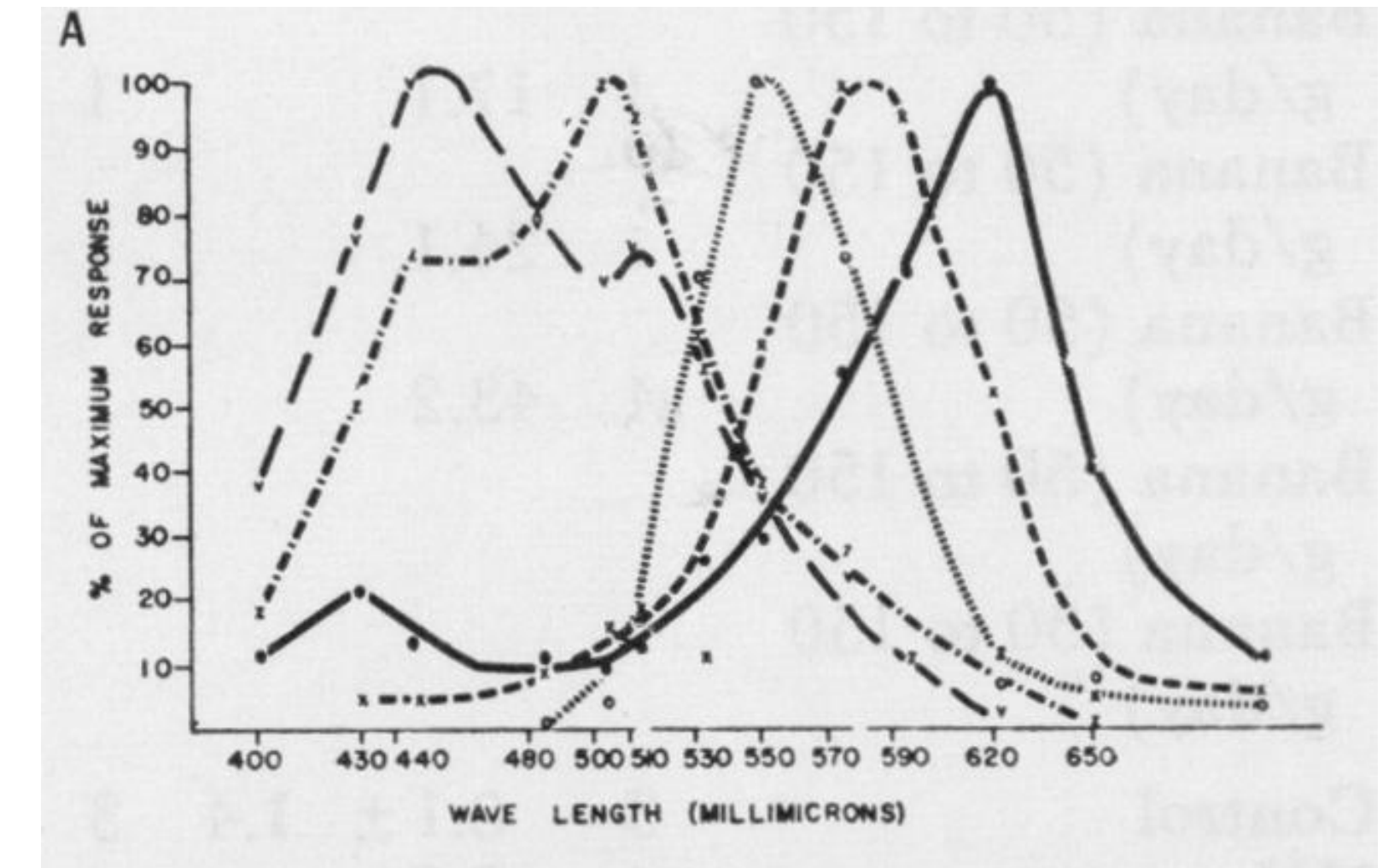
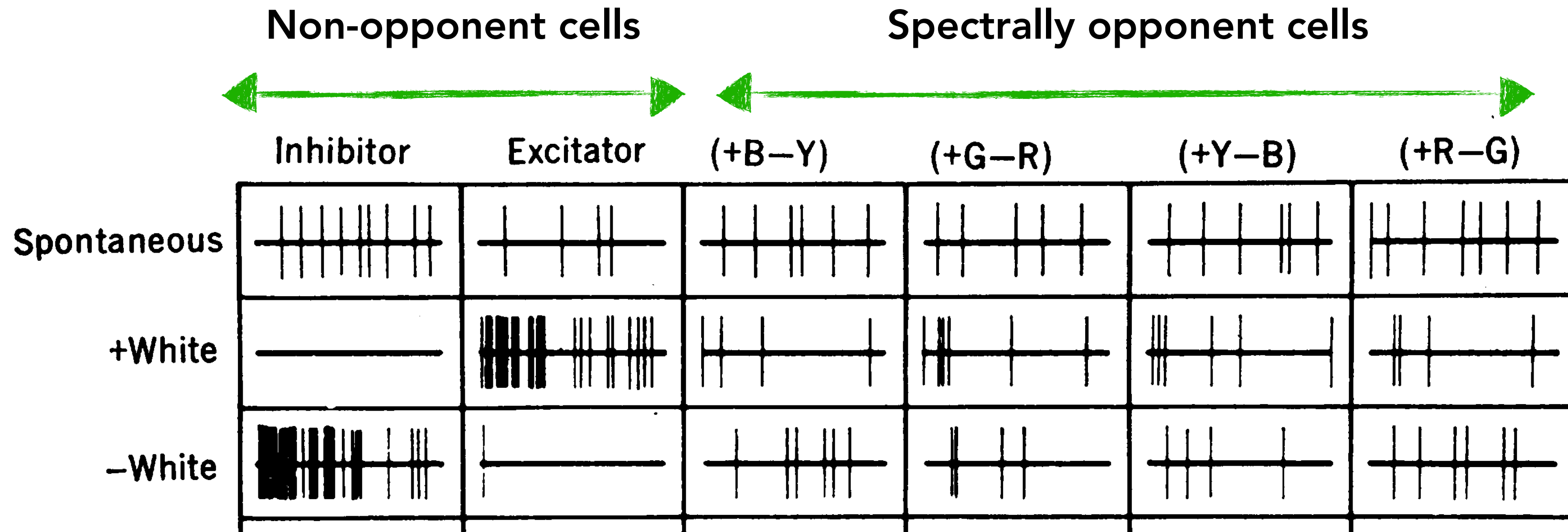
Spectrally-Opponent Cells in LGN (~ = RGCs)

*on macaques; different curves represent different light intensities



Non-Opponent LGN Neurons (\approx RGCs)

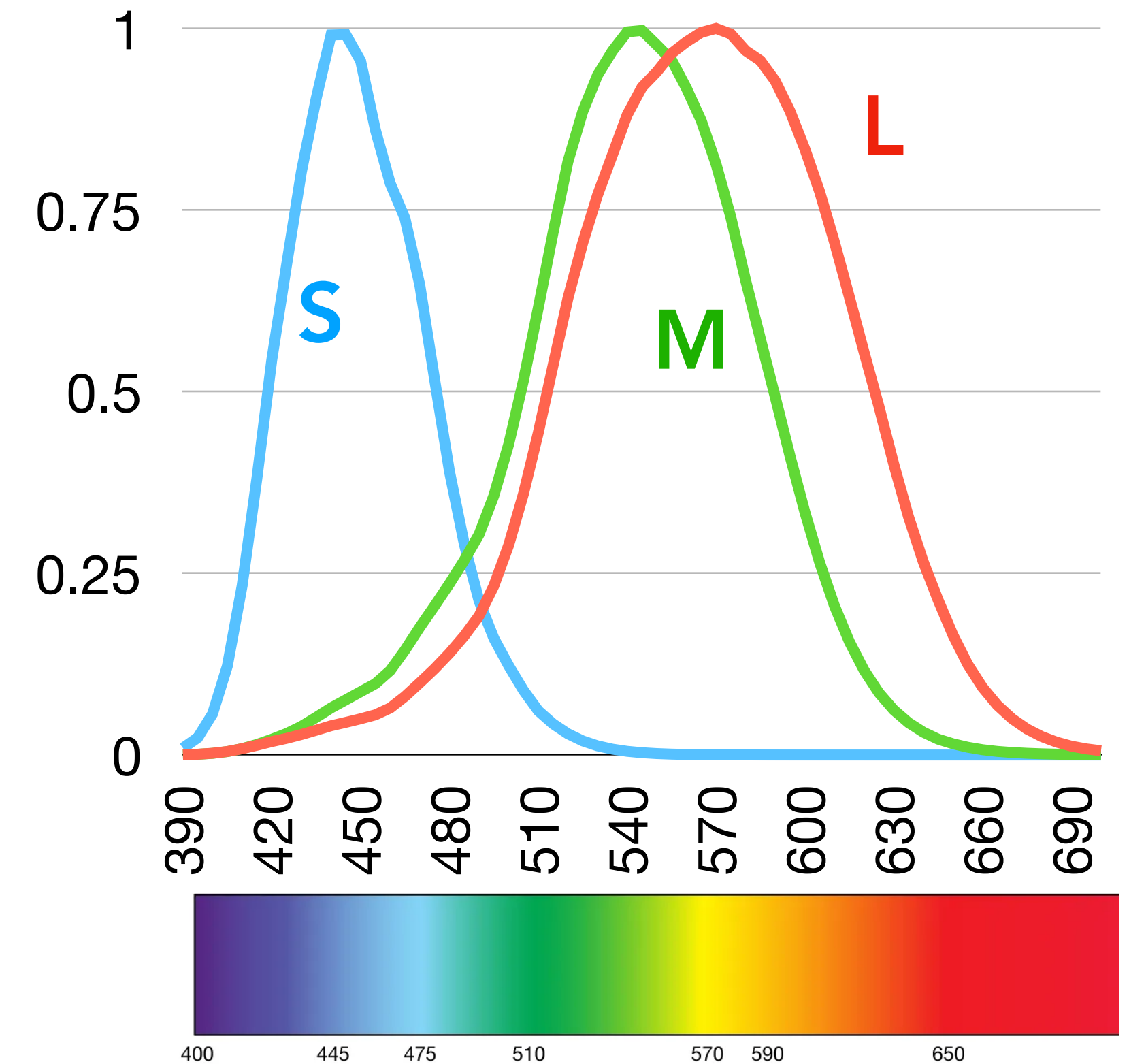
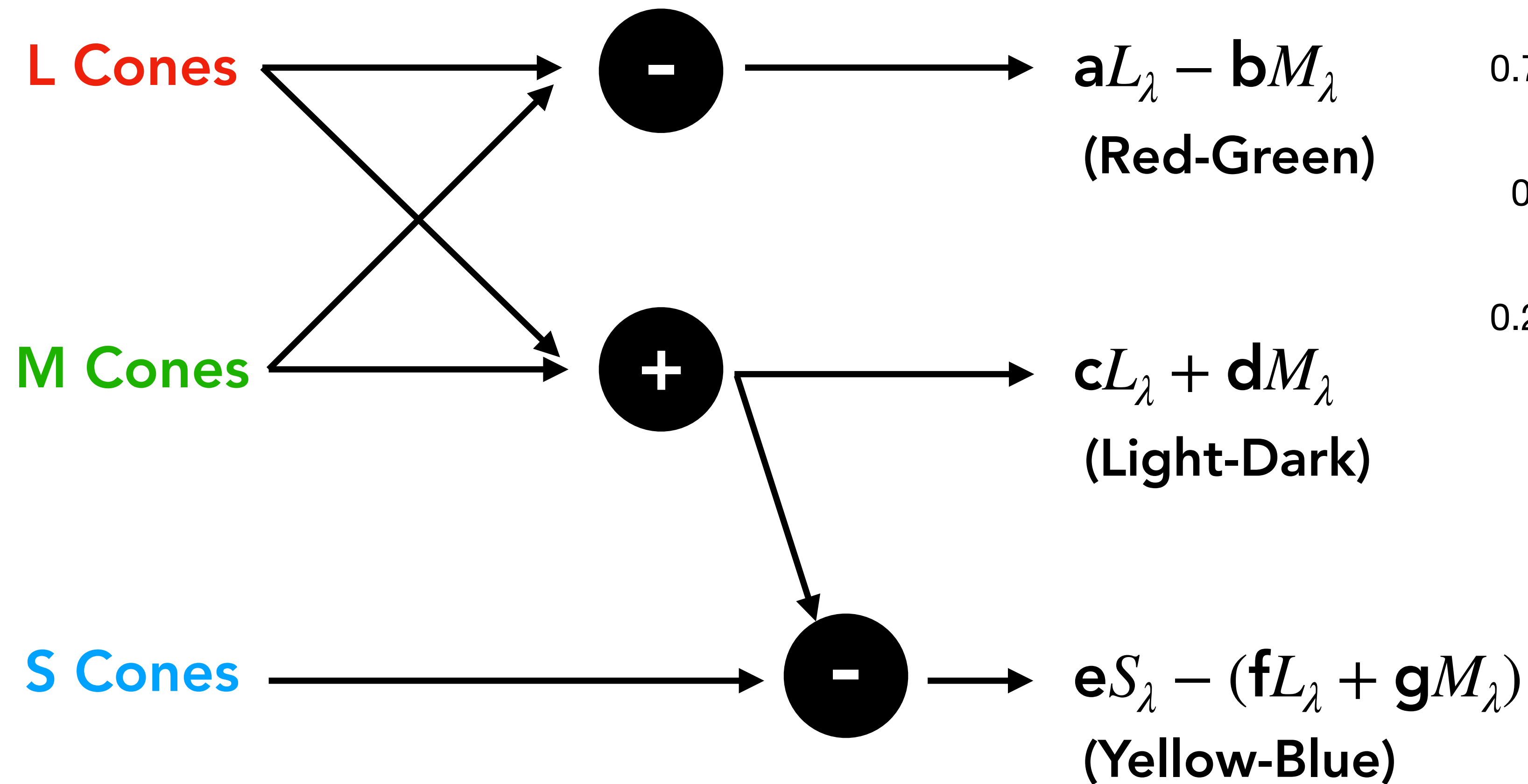
*on macaques



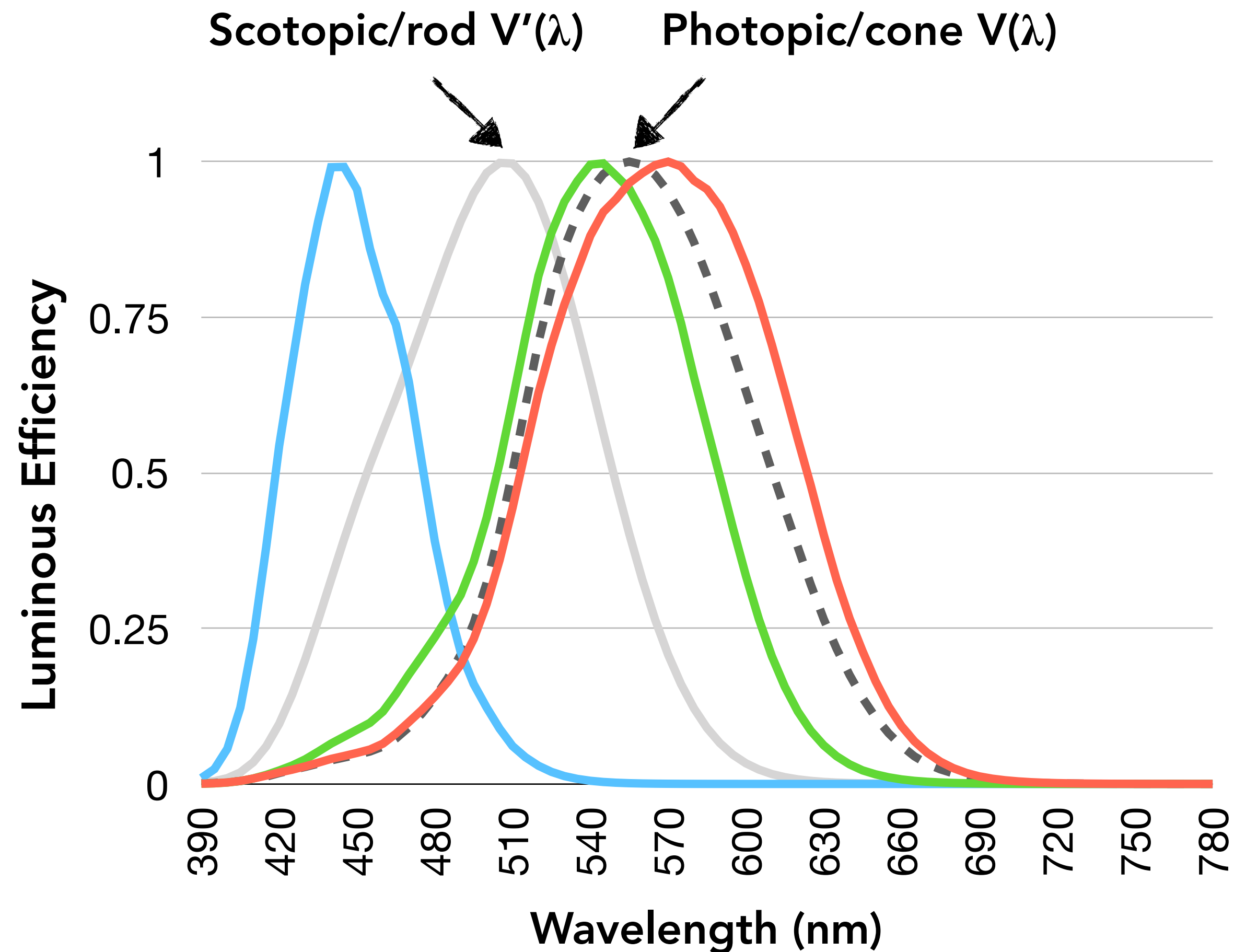
- De Valois et al. also found LGN neurons that give only ON (or OFF) responses to all wavelengths; they are non-opponent cells.
- Spectrally opponent cells do not respond to white lights (with all wavelengths present).

A Conceptual, Functional Model

* Stage Theory in color science parlance



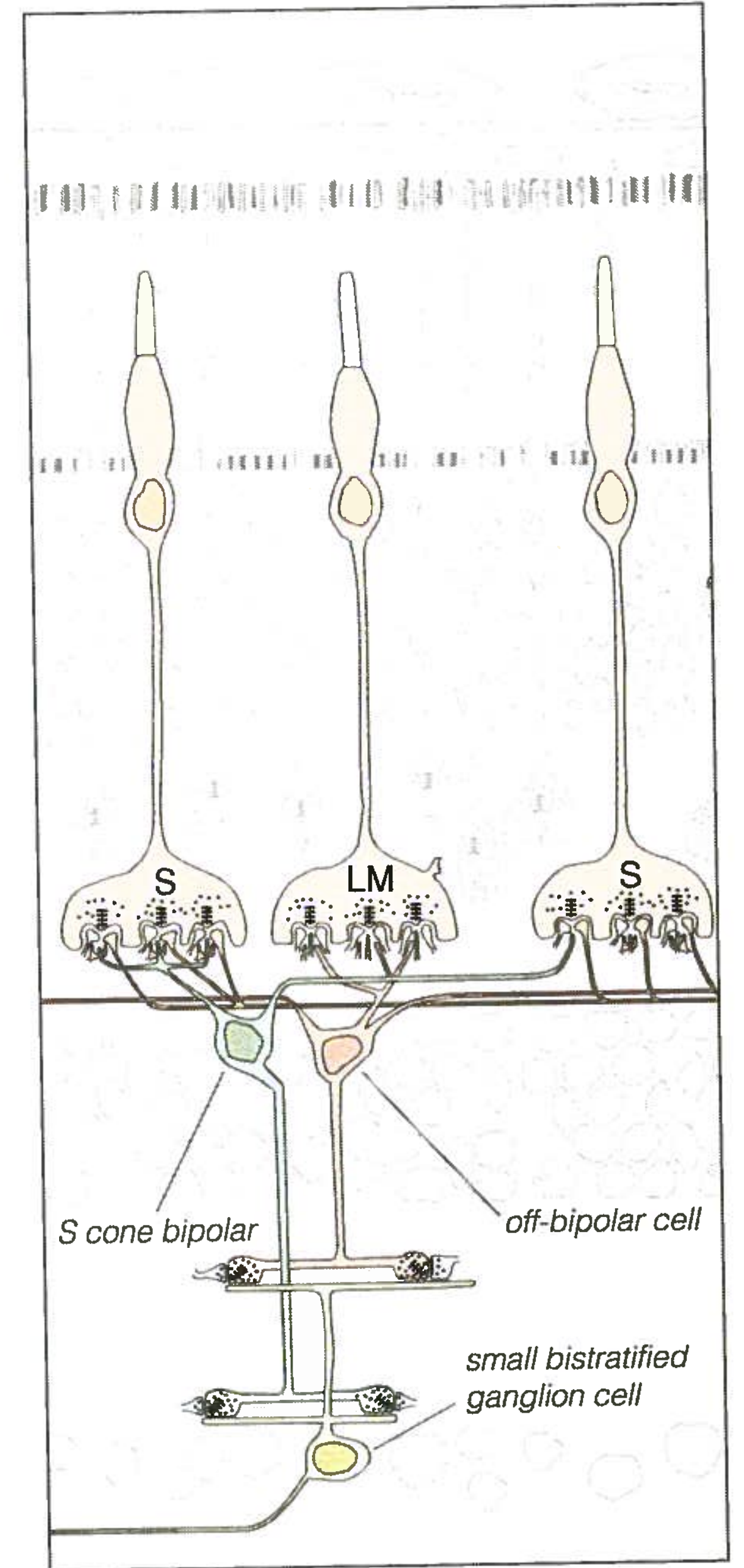
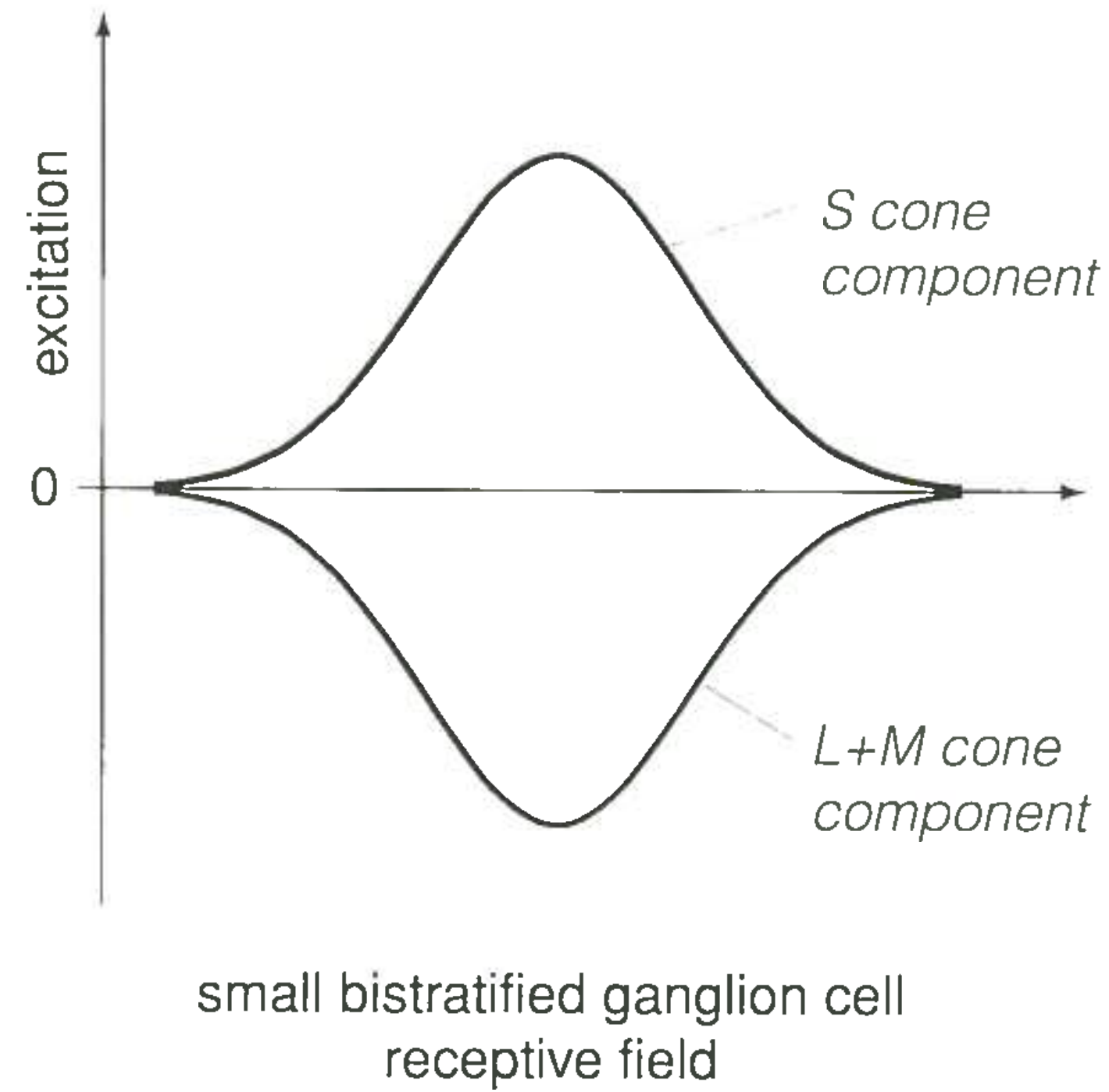
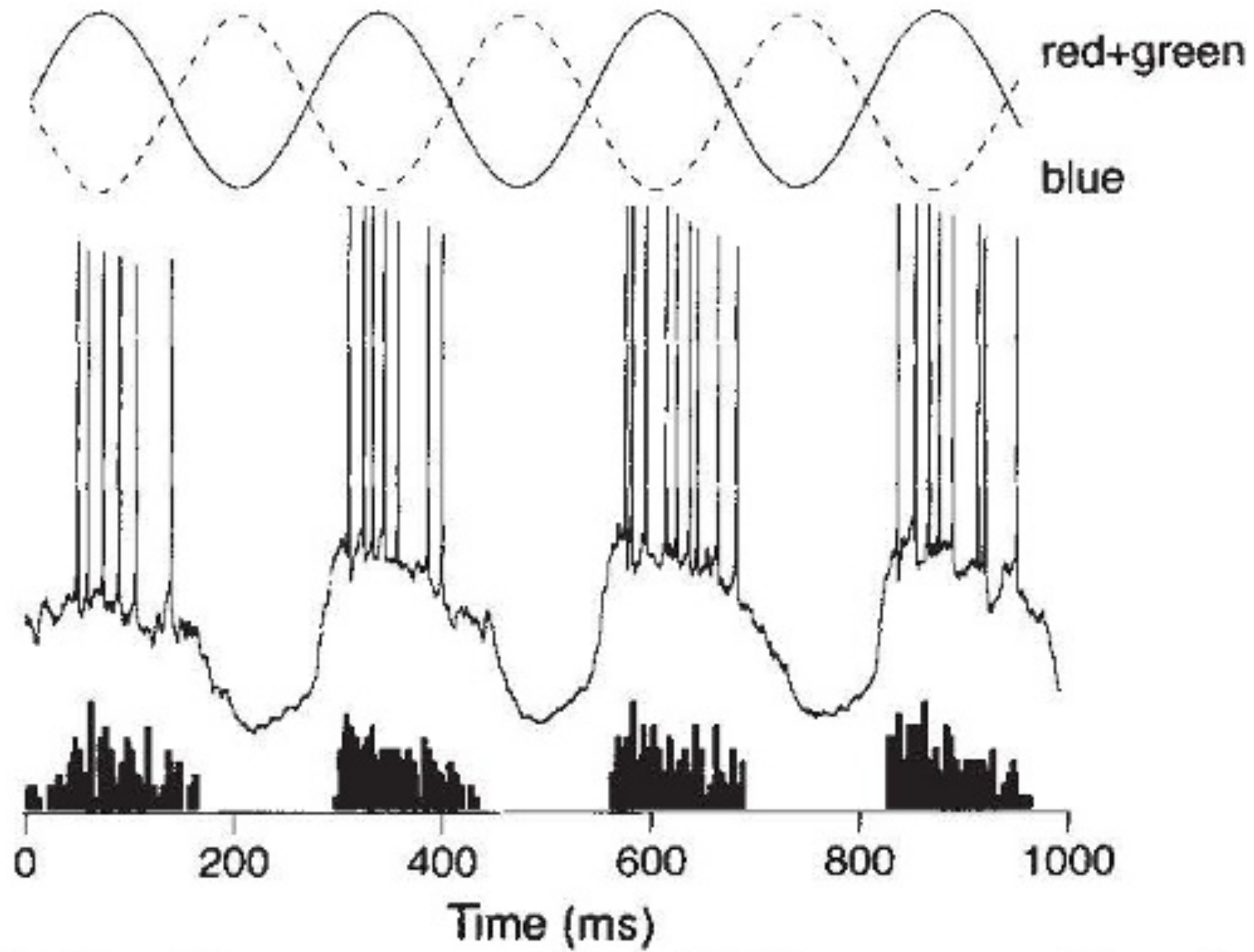
Photopic Luminous Efficiency Function $\approx L + M$



- Photopic luminous efficiency function is experimentally fit well with a positive linear combination of L cone responses and M cone responses
 - Usually in an about 2:1 ratio
 - S cone responses seem to make very little, if any, contribution to our luminance perception

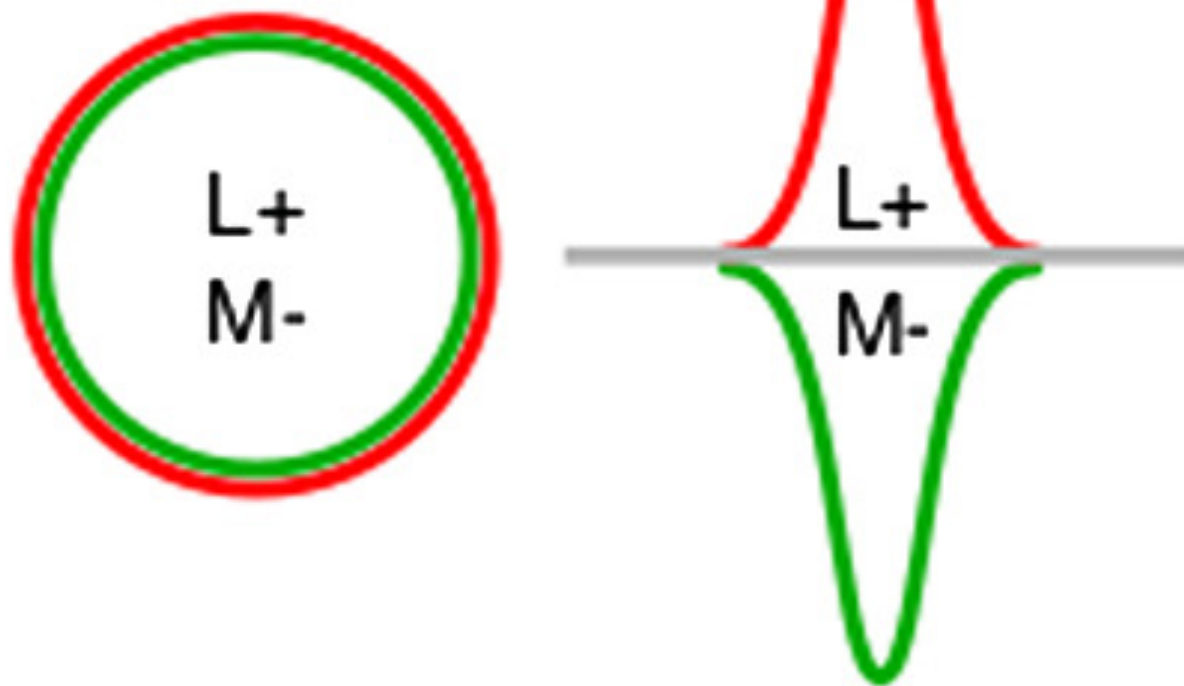
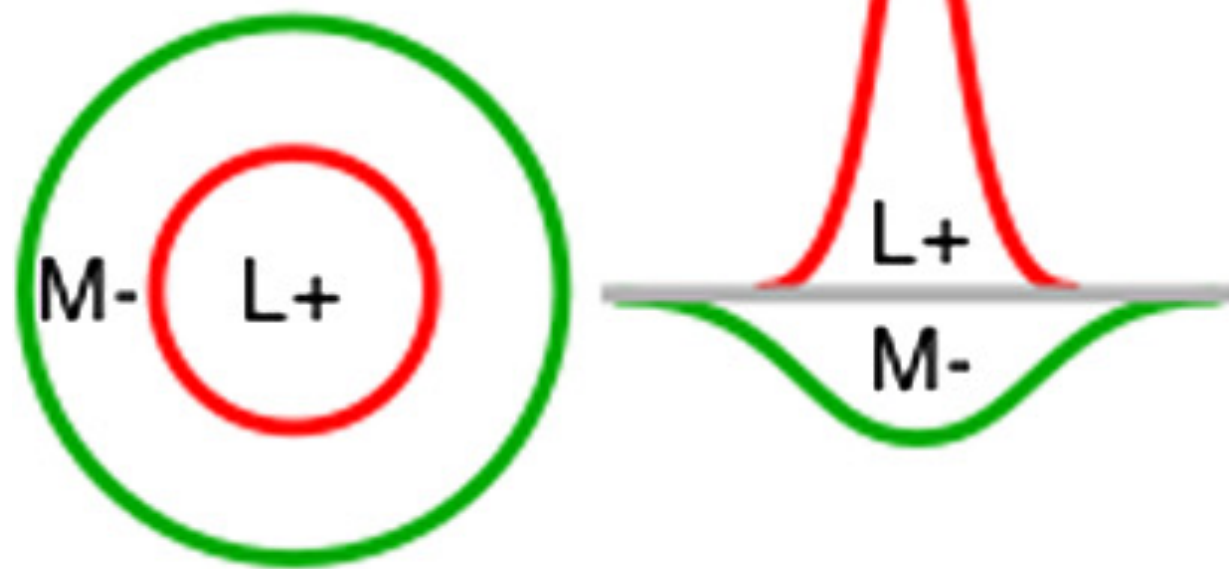
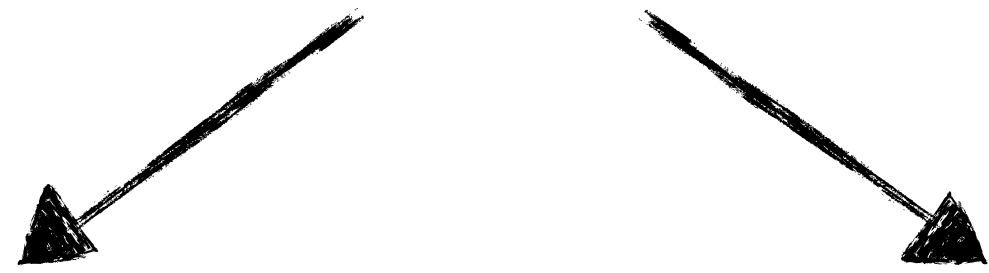
Potential S-(L+M) Pathway

Small Bistratified RGCs; Blue-On, Yellow-Off here; center only



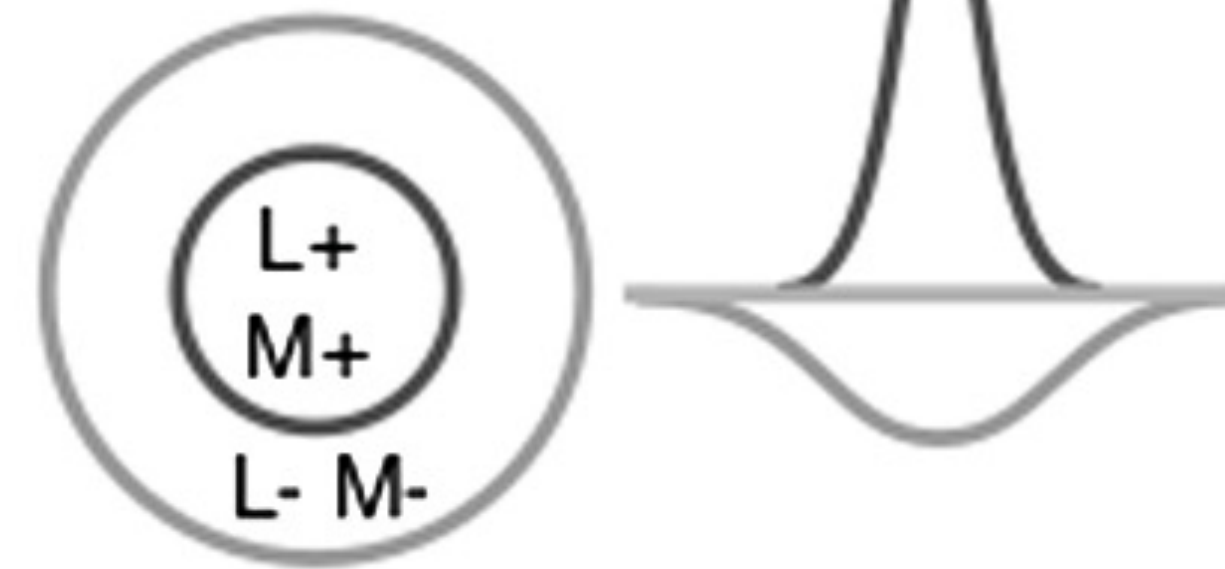
Potential R-G and Light-Dark Pathways

Most Midget RGCs

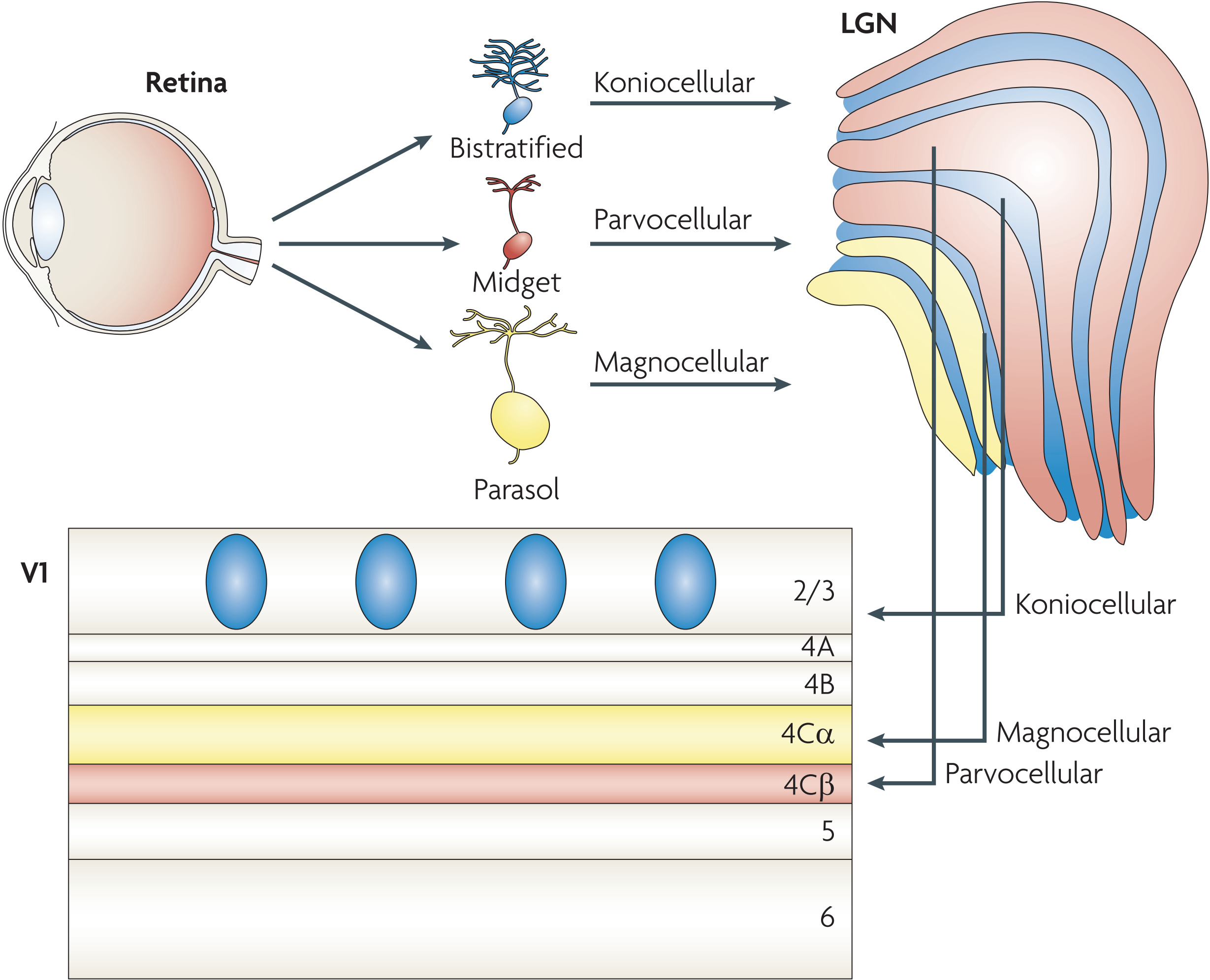
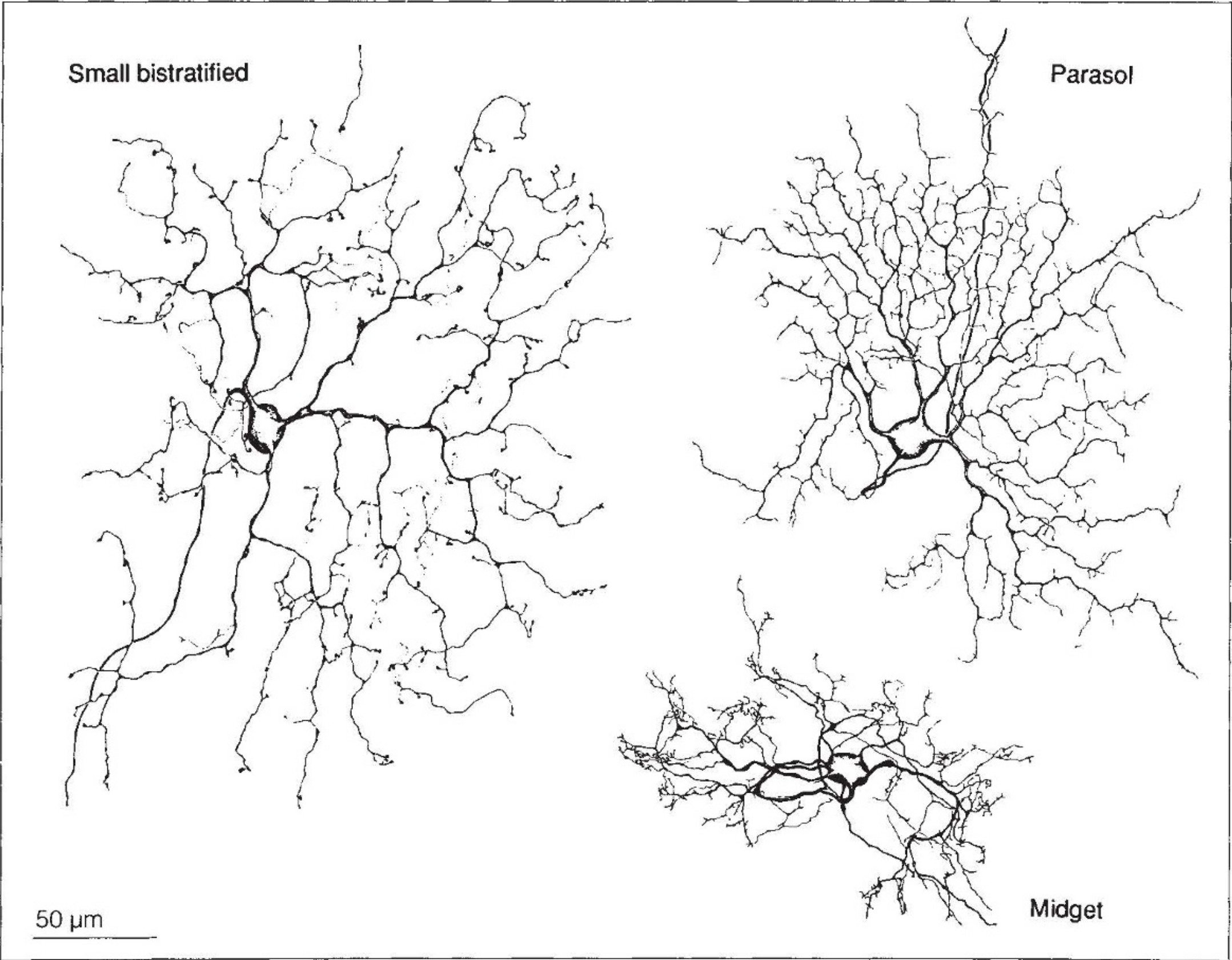


All four combinations exist
(L-M+, L+M-, M+L-, M-L+)

Some Midget RGCs
and All Parasol RGCs



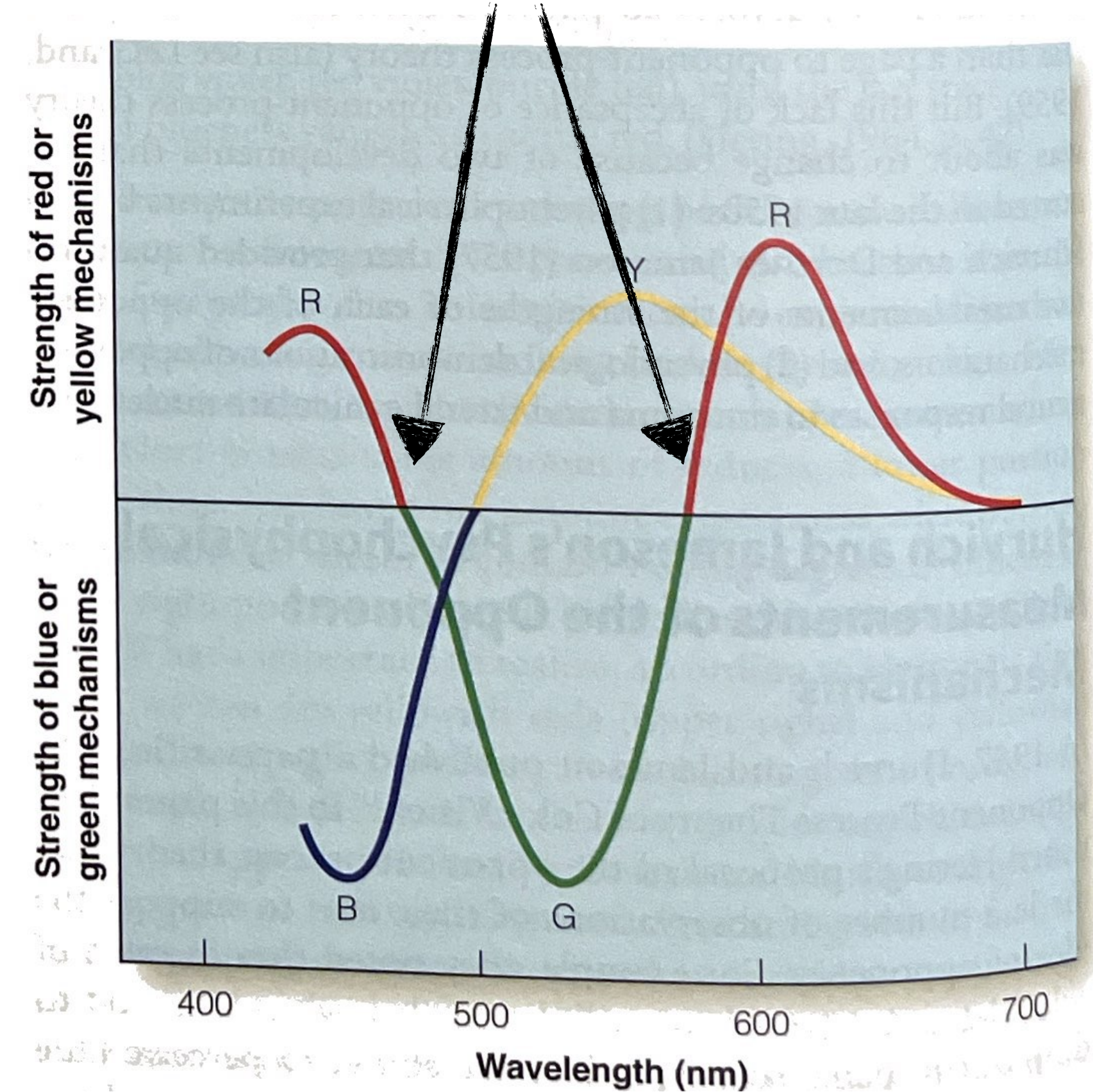
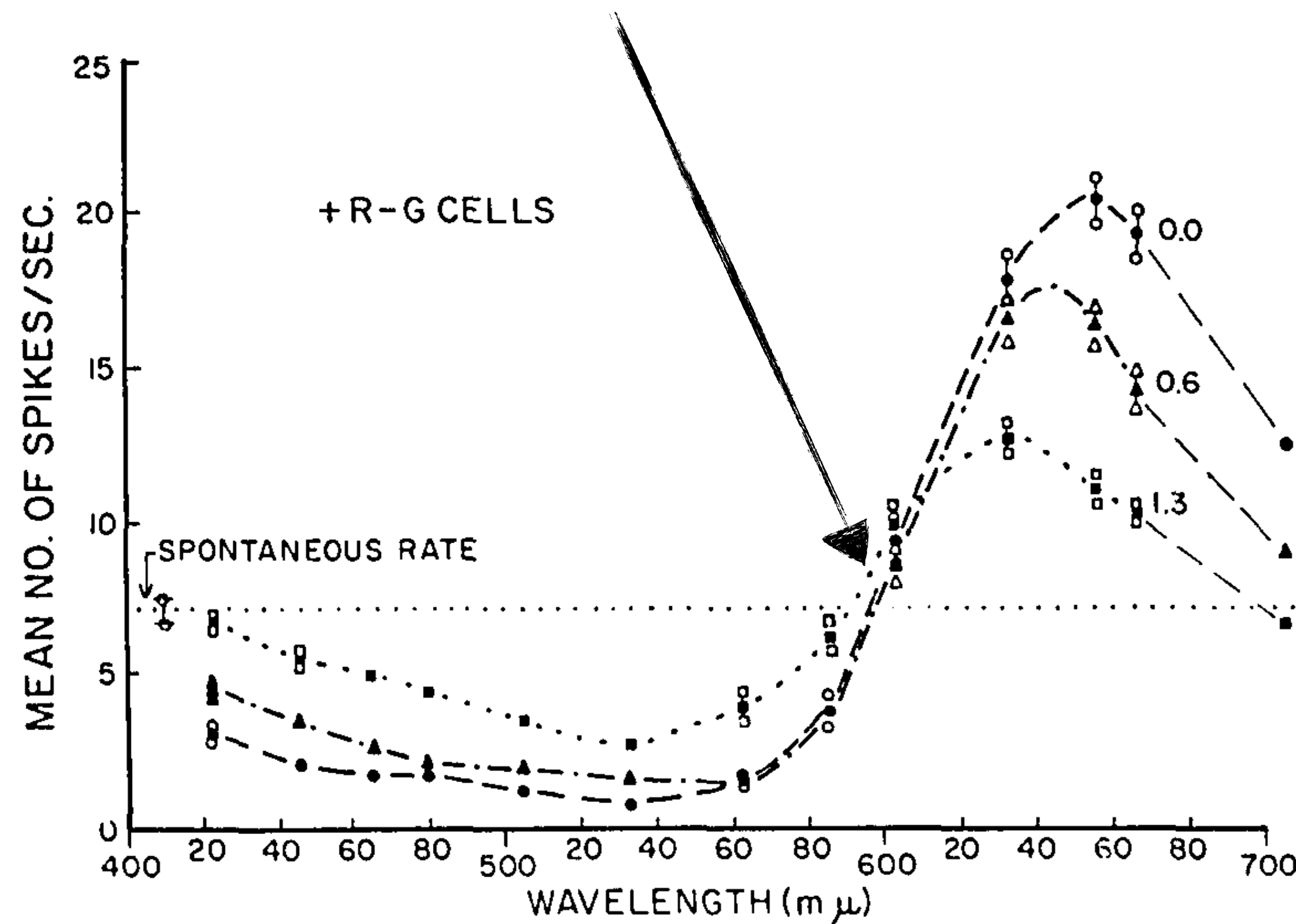
Parallel Pathways For Color?



Caveat 1: Correlations are Weak

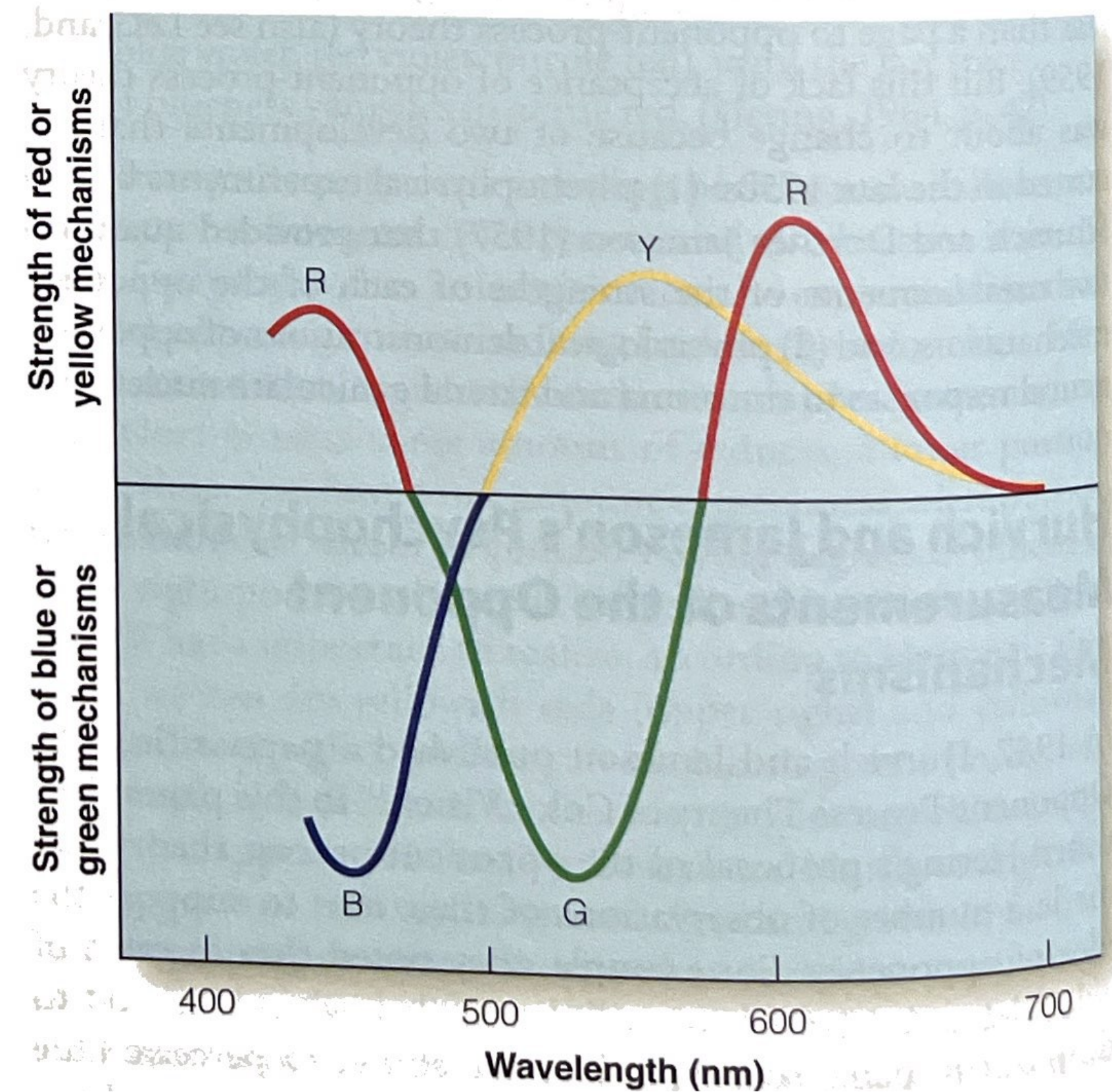
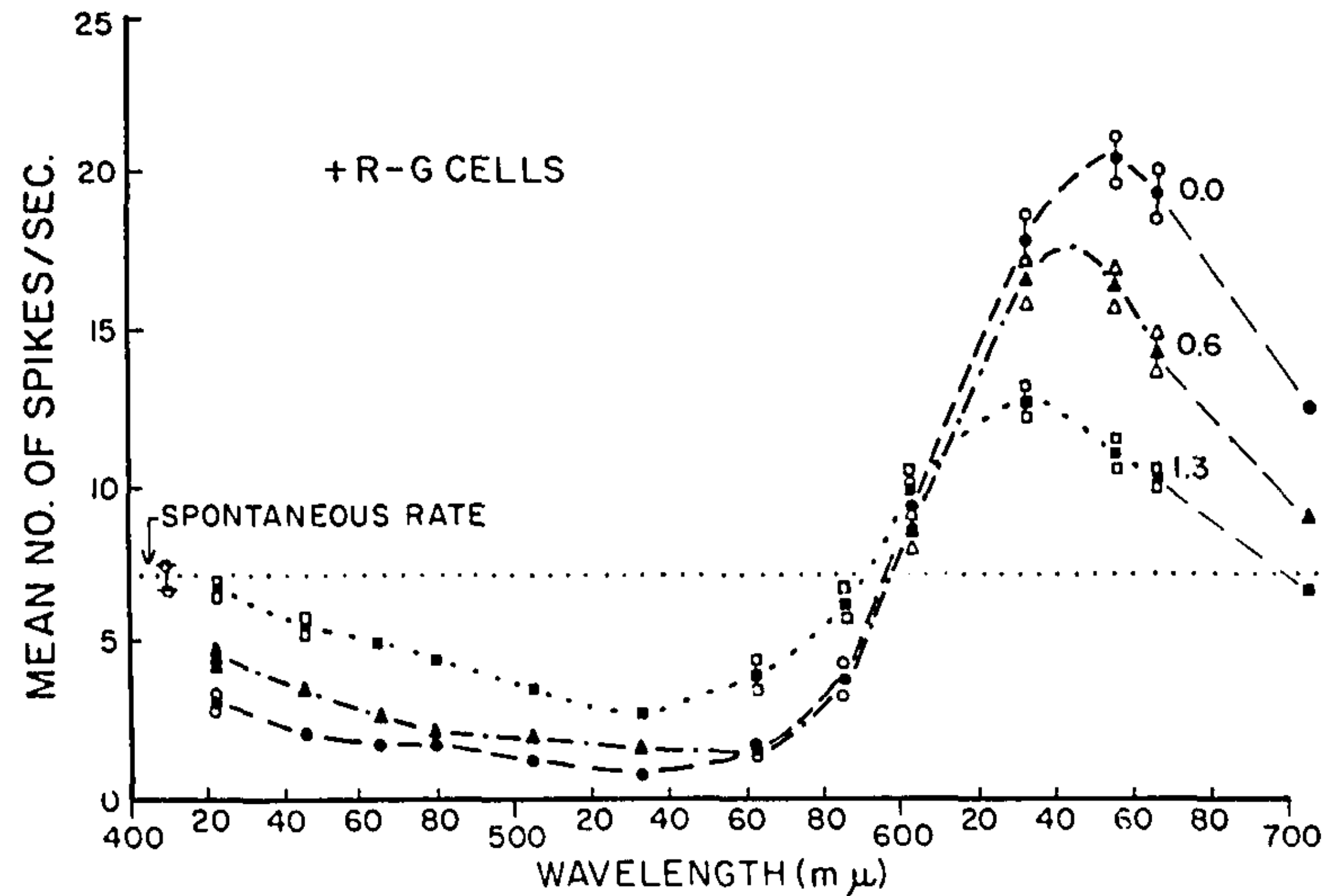
The R-G opponent neurons have only one zero crossing, so they can't explain why humans see red in low-wavelength lights

The psychophysical R-G curve has two zero crossings; we need neurons that exhibit L-M+S to explain the positive R in short-wavelength, but no neuron seems to have that property



Caveat 1: Correlations are Weak

- No single neuron population's profile perfectly matches behavioral results
 - These neurons **contribute** to opponent process, but no one directly **causes** it

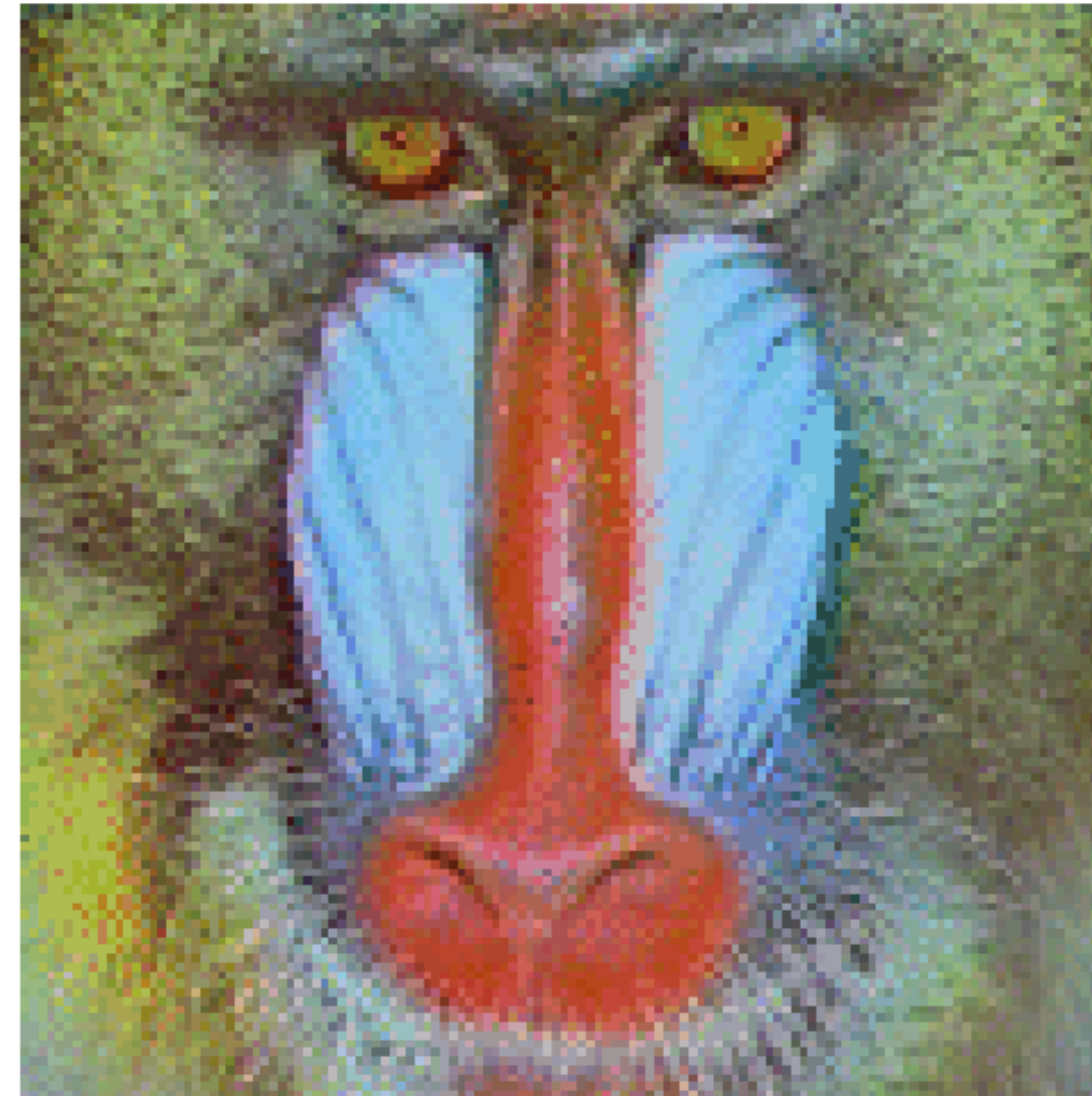


Caveat 2: Parasol Pathway \neq Luminance Channel

Blur dark-light channel



Blur red-green channel

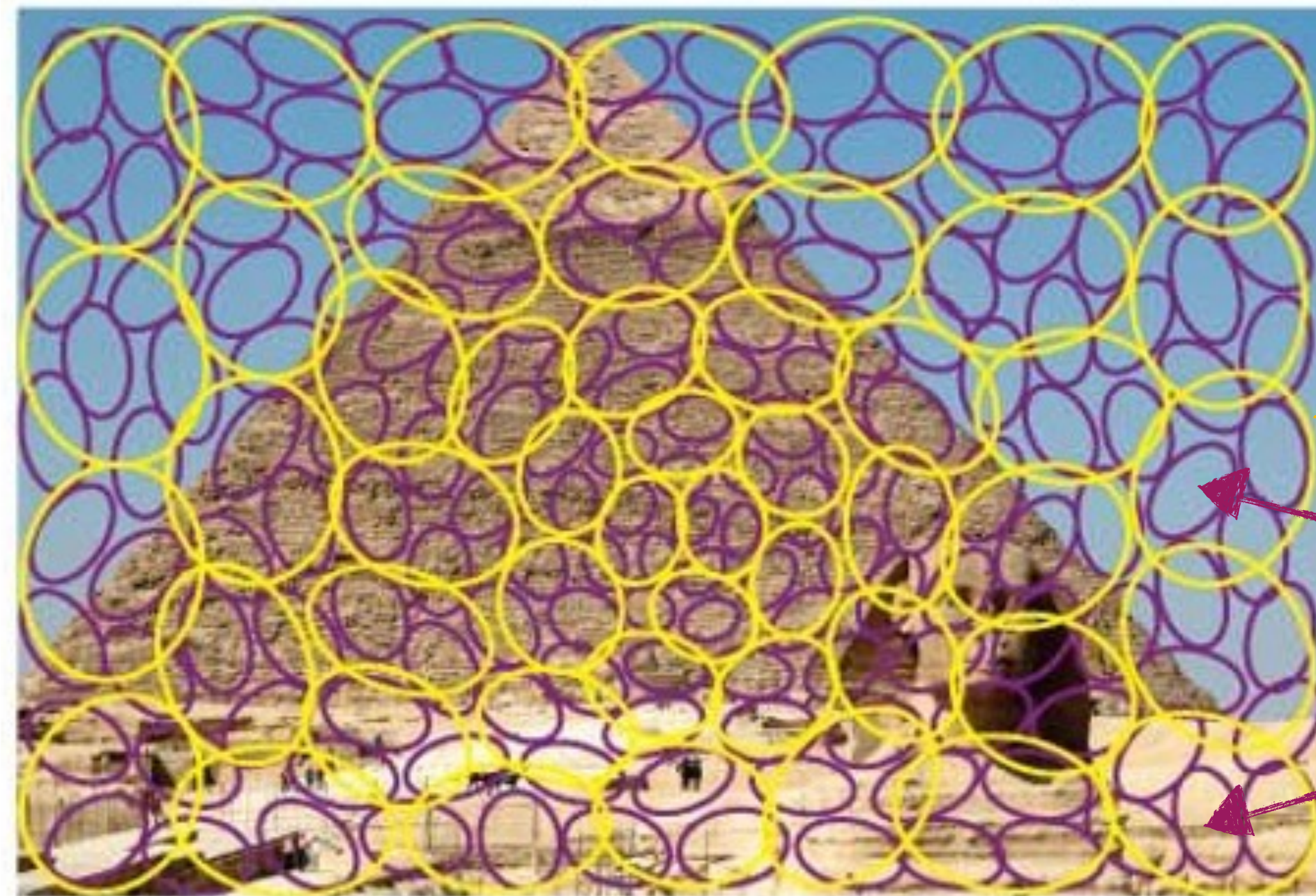


Blur yellow-blue channel



- HVS is sensitive to blurring in dark-light channel
 - Basis for chroma subsampling in model video codec (later in the class)
 - But this also means Parasol RGCs alone can't explain luminance, since Parasol cells have large receptive fields (low-pass filters).

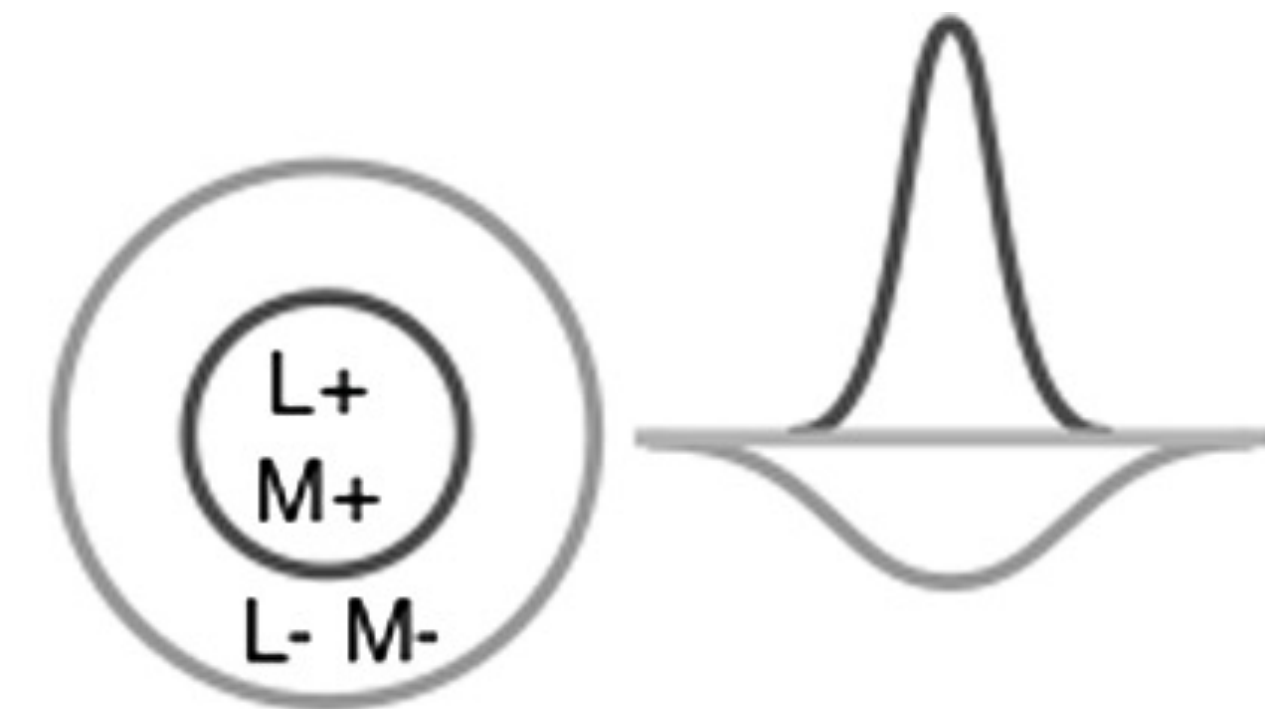
Caveat 2: Parasol Pathway != Luminance Channel



Parasol RFs

Midget RFs

All Parasol RGCs



- Parasol RGCs clearly contribute to luminance perception, but luminance perception also requires high spatial resolution, which parasol RGCs don't have but Midget RGCs do: likely multiple mechanisms are involved.

Key Things to Take Away

- The cone cells are the first stage of color encoding, where they turn spectral power distribution in light to cone responses
- Since there are three cone classes, color vision is trichromatic
 - Light spectrum is encoded into a three-dimensional space, so any color can *in theory* be produced from mixing three other colors (subject to gamut limit)
- **Metamerism: lights having different spectra but the same color.**
 - This is because color encoding by photoreceptors is a huge dimensionality reduction
 - Metamerism explains color matching experiments, which is an experimental demonstration of trichromatic theory of color

Key Things to Take Away

- The opponent processes are the second stage of color encoding, where cone responses seemingly are turned into a red-green channel, a yellow-blue channel, and a dark-light channel
- Our brain seems to perform a **perceptual color mixing** using the three opponent channels
- While color trichromacy has a perfect neural basis, there is no single pathway that explains any of the three opponent processes; still an open research question
 - although there are definitely neurons that seem to have what it takes to serve the R-G, Y-B, and light-dark opponent processes.