

Fundamentals of Color and Appearance

Module 7

Color Scales and Color Differences

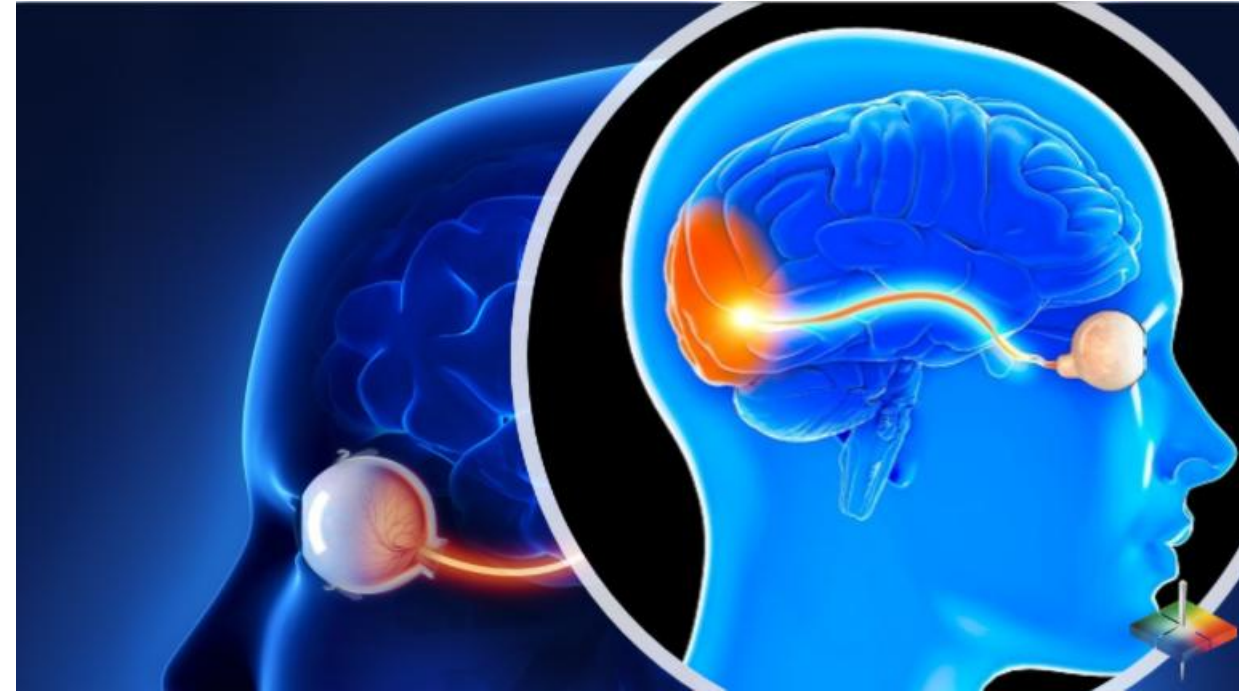
Color Science Educational Series



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Human color perception is fundamentally rooted in human biology. One of the most influential models that explains how our visual system processes color is the **Opponent Color Theory**.

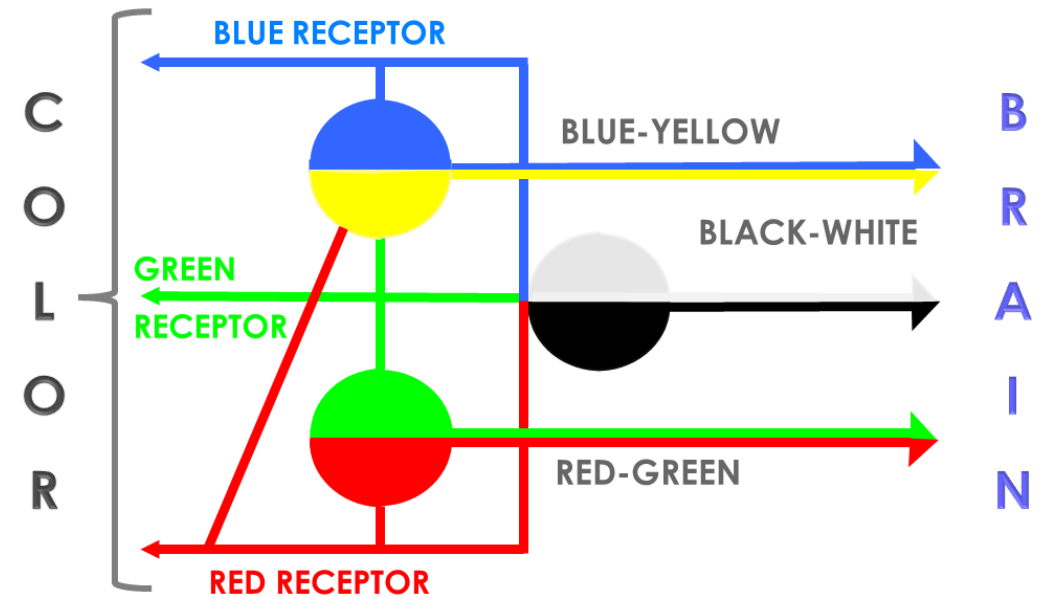




The **opponent process** interprets information about color by processing signals from photoreceptor cells in an antagonistic manner.

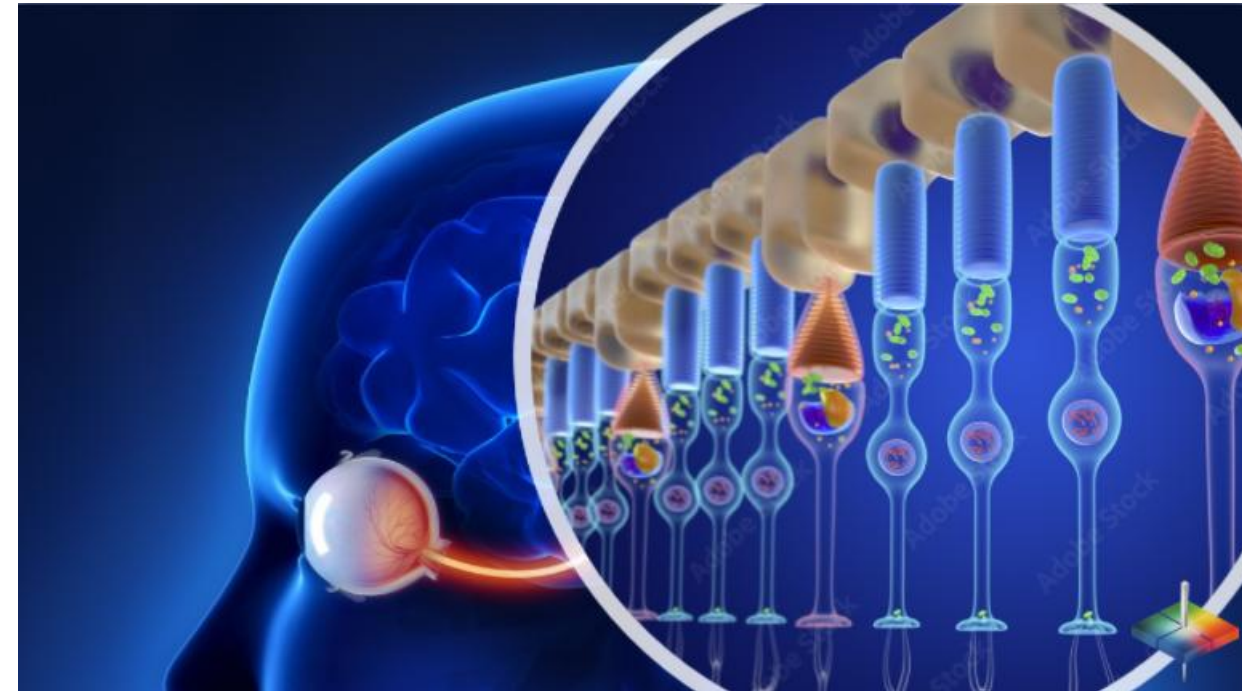
The opponent-process theory suggests that there are three opponent channels, each comprising an opposing color pair: **red versus green**, **blue versus yellow**, and **black versus white** (luminance).

When staring at a bright color for a while (e.g. red), then looking away at a white field, an afterimage is perceived, such that the original color will evoke its complementary color (green, in the case of red input).



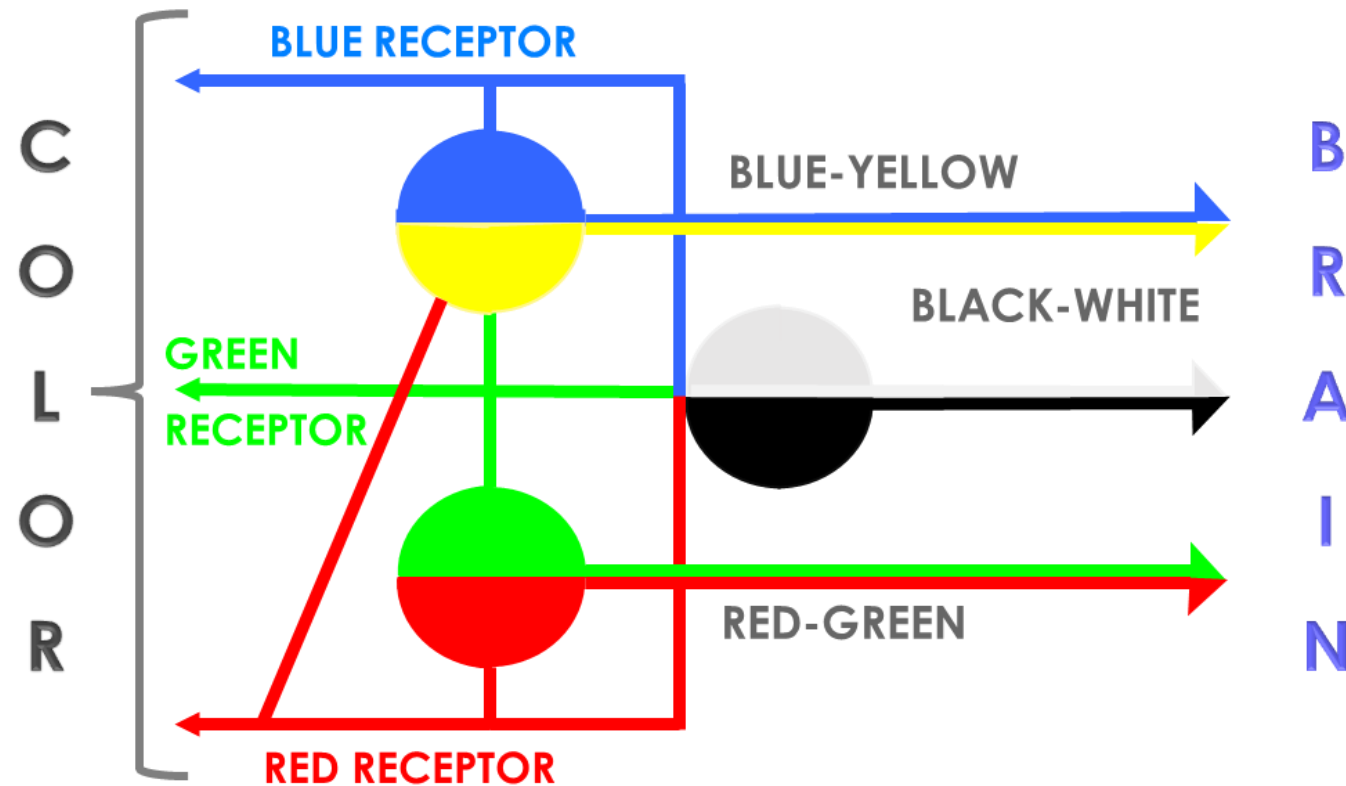


According to this theory, color perception arises not just from individual signals sent to our brains by the three types of cone photoreceptors in our eyes, but also from how these signals are compared and processed antagonistically in the visual system.



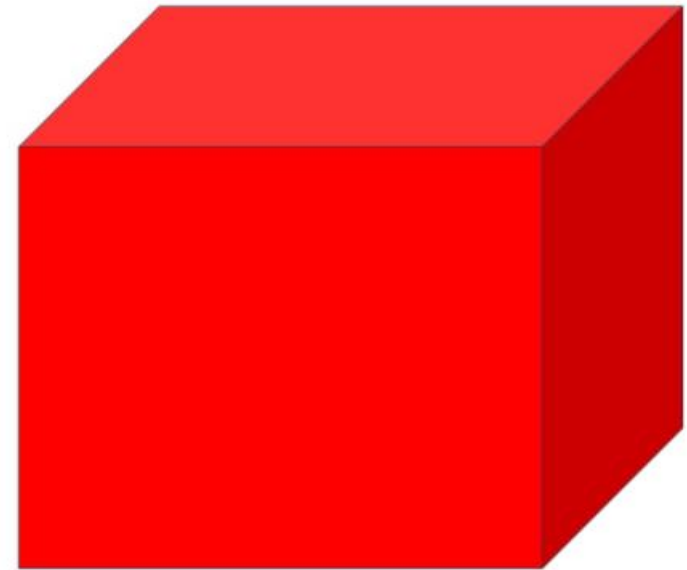


The **Opponent-Color Theory** states that the eye's red, green, and blue photoreceptor response functions are combined into opposing channels





If you stare at a bright red object for an extended period

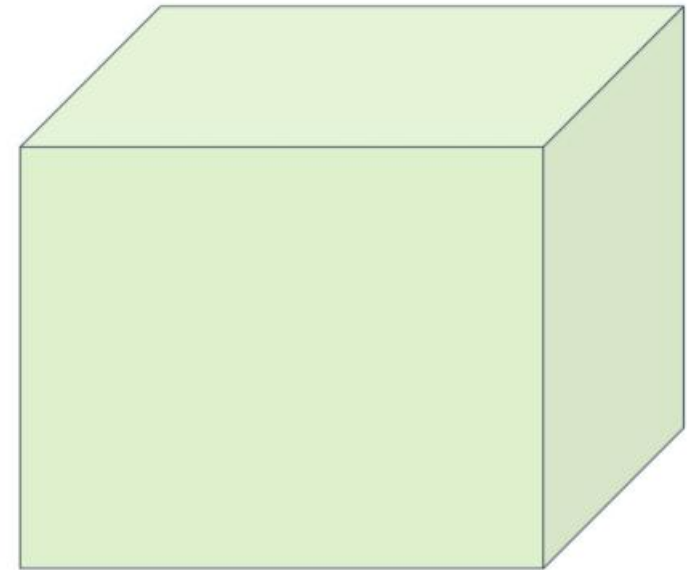




And then shift your gaze to a white surface.



You'll see a green afterimage, the brain's way of rebalancing the overstimulated opponent channel.





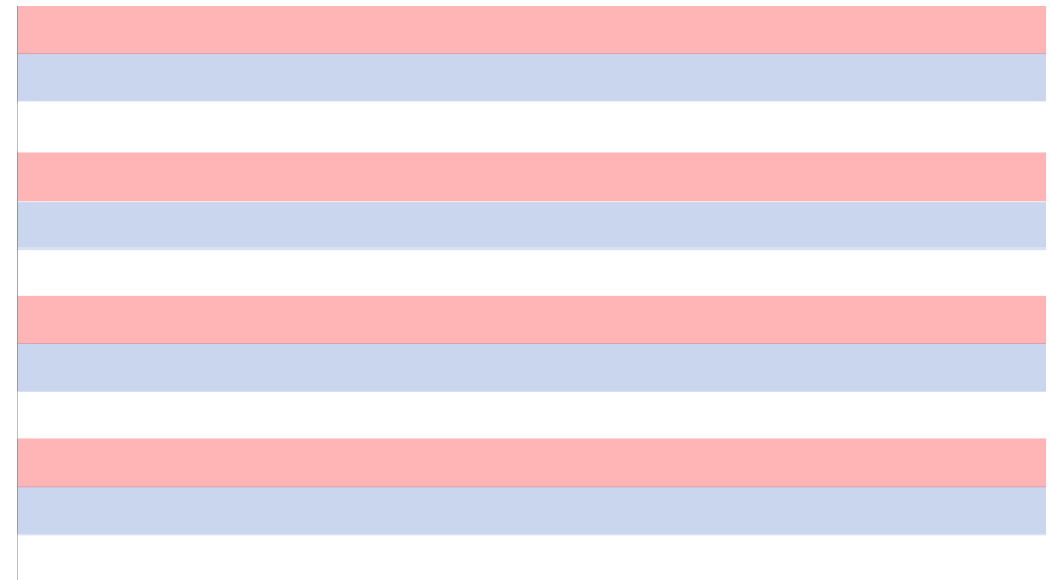
When the next slide appears, focus on the black cross in the center of the stripes until the slide automatically changes to the white screen.



Did you see the stripes as red, white and blue?

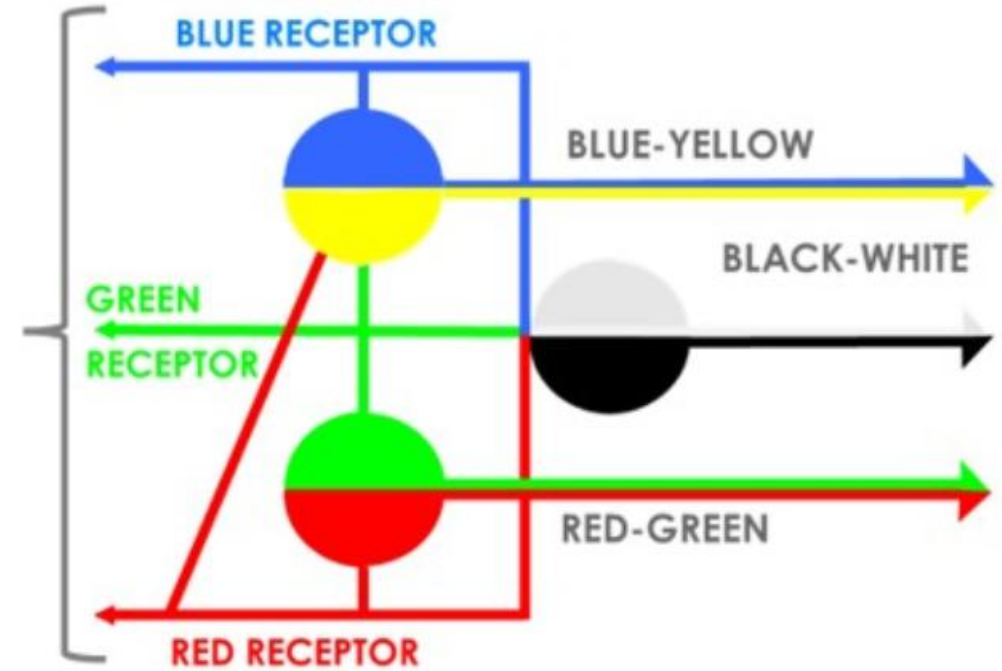
This happens because the green, black and yellow stripes saturate the cone responses.

When you look at the blank screen your vision tries to return to balance, and you see a red, white and blue after-image.





This illustrates the opponent color theory and demonstrates how our eyes strive to maintain balance. Saturated cone responses temporarily suppress one side of the opponent pair. As the visual system resets, we see the complementary color emerge, validating the opponent process mechanism.





The color opponent theory is yet another important concept that contributes to modern color science, so before we move on to learn about color scales, color differences, color tolerances, and other important topics discussed in the remainder of this series, so let's recap what we have learned so far:



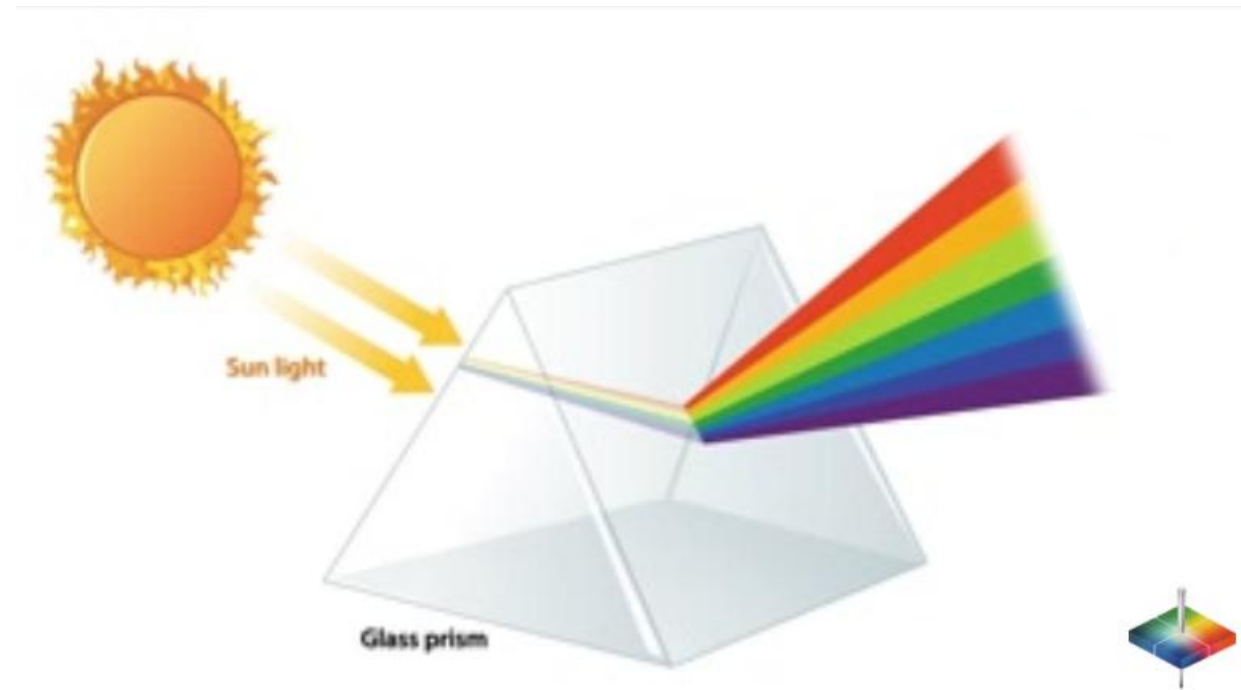


In Module 2, **How we see Color**, we learned about the physics, the chemistry, and the biology behind how humans see and perceive color, starting with the physics of light.



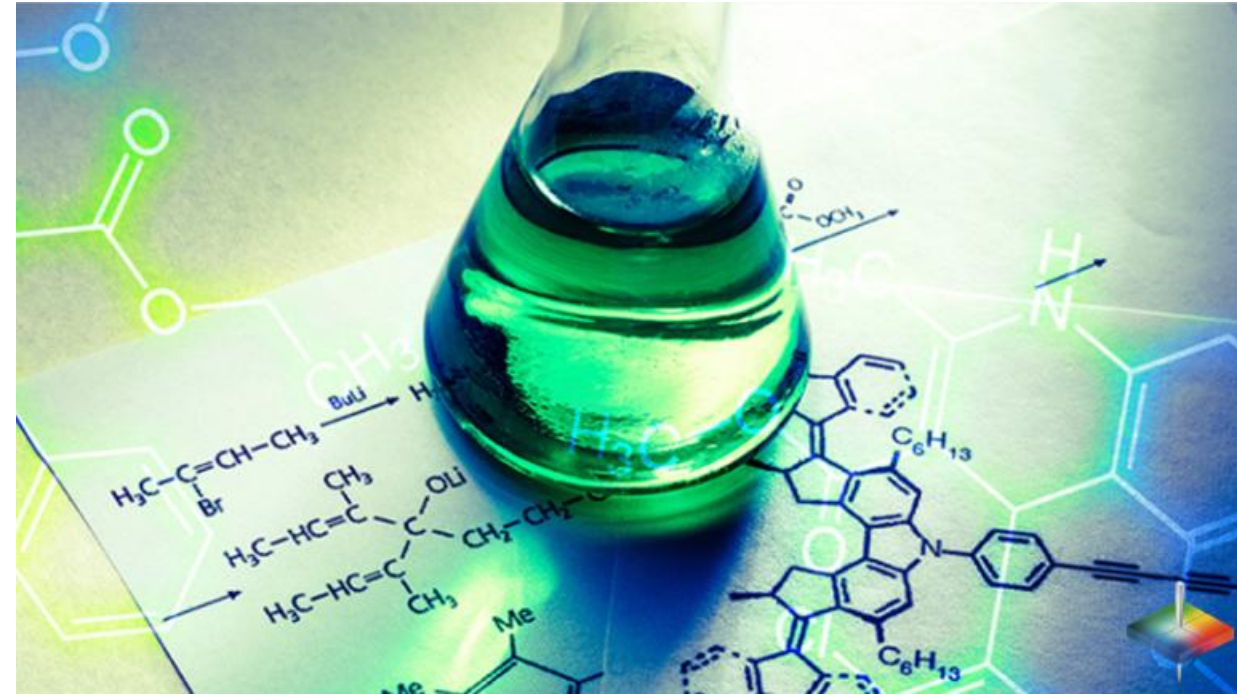


We learned how **Sir Isaac Newton** demonstrated that white light is composed of multiple component colors by passing it through a prism. This process, known as dispersion, revealed the visible spectrum, consisting of **Red, Orange, Yellow, Green, Blue, Indigo, and Violet**.





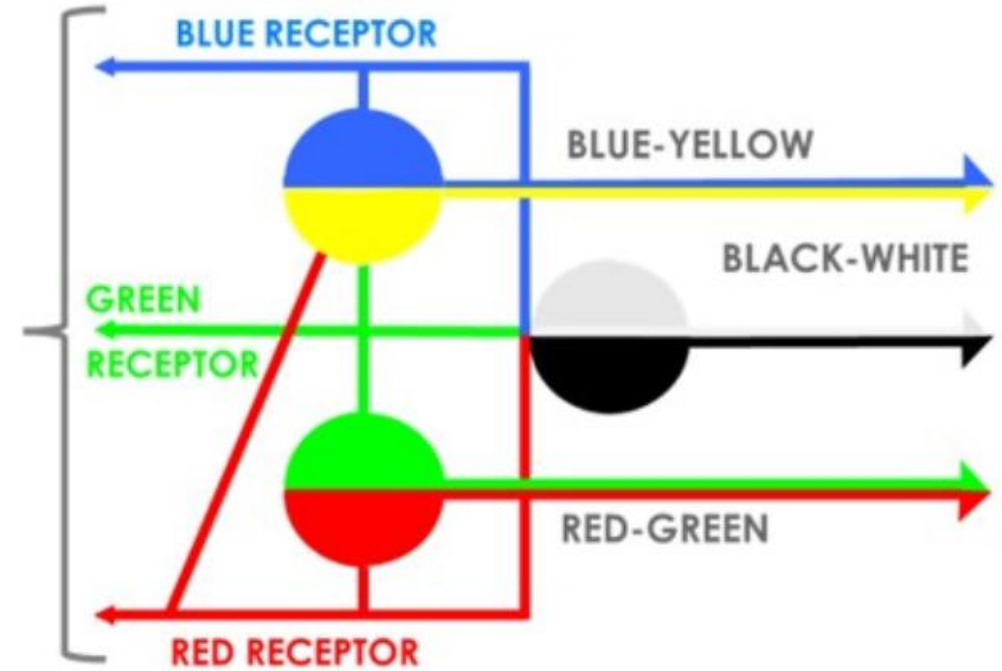
We also learned that matter does not possess color, but rather, that the colors we see are the result of how light interacts with the chemical compositions of matter.





We've now learned about the **Opponent Color Theory** which proposes that the human eye interprets color through opposing neural mechanisms, forming three opponent channels:

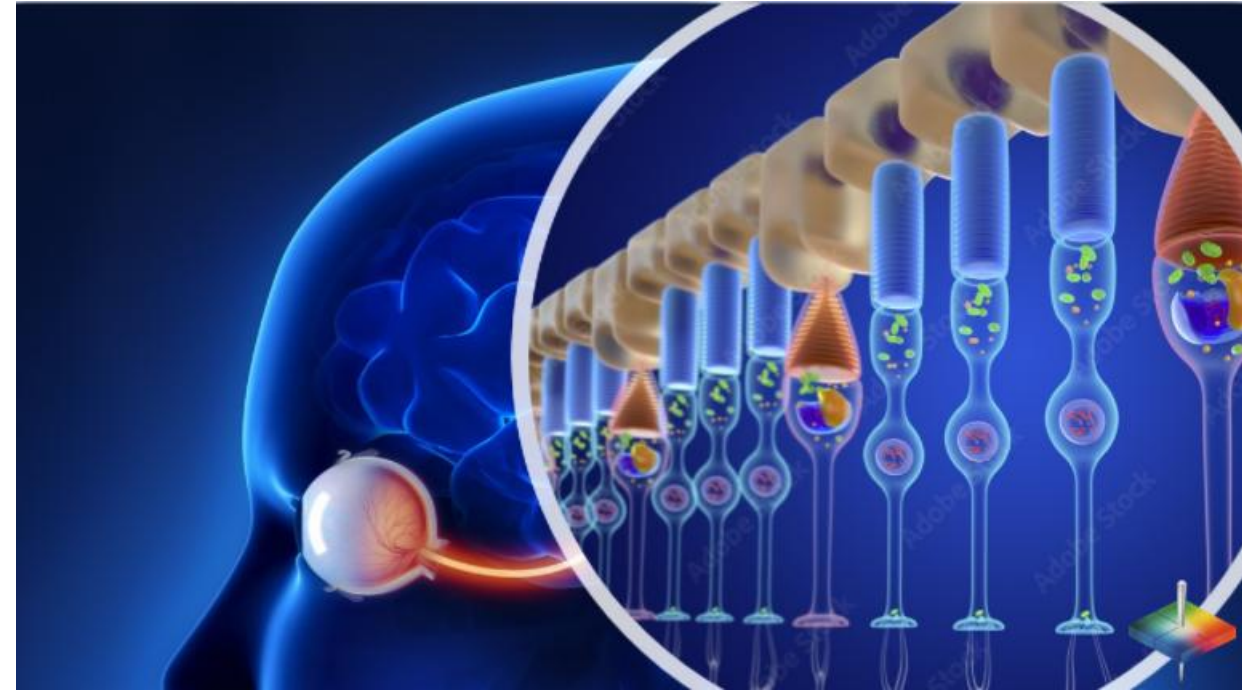
- Red verses Green.
- Blue verses Yellow.
- Black verses White.



Color Scales and Color Differences

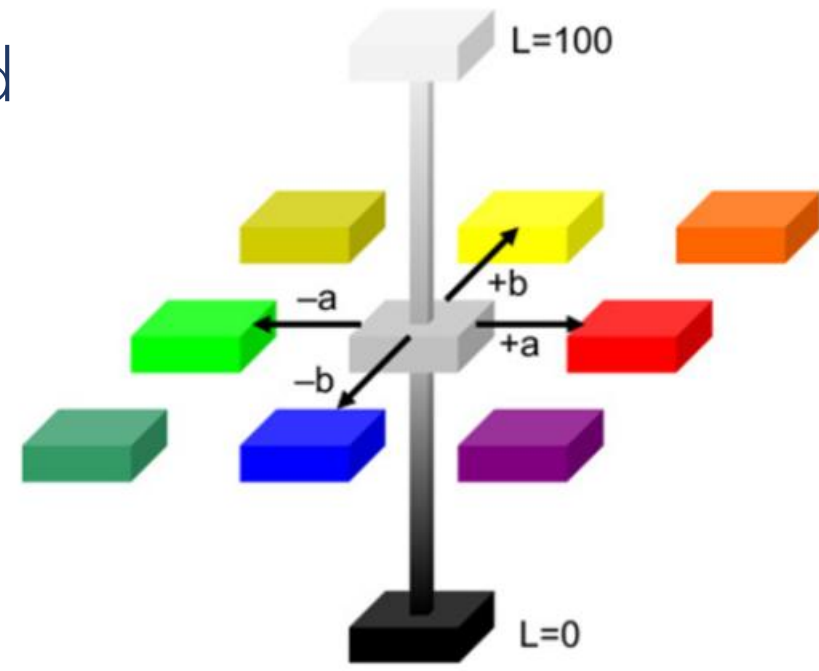


The eye's red, green, and blue cone response functions are neurologically organized into these opponent pairs, allowing us to detect contrasts and perceive a wide range of colors. This understanding helps us appreciate the structure of the L,a,b color space, used extensively in modern color measurement.





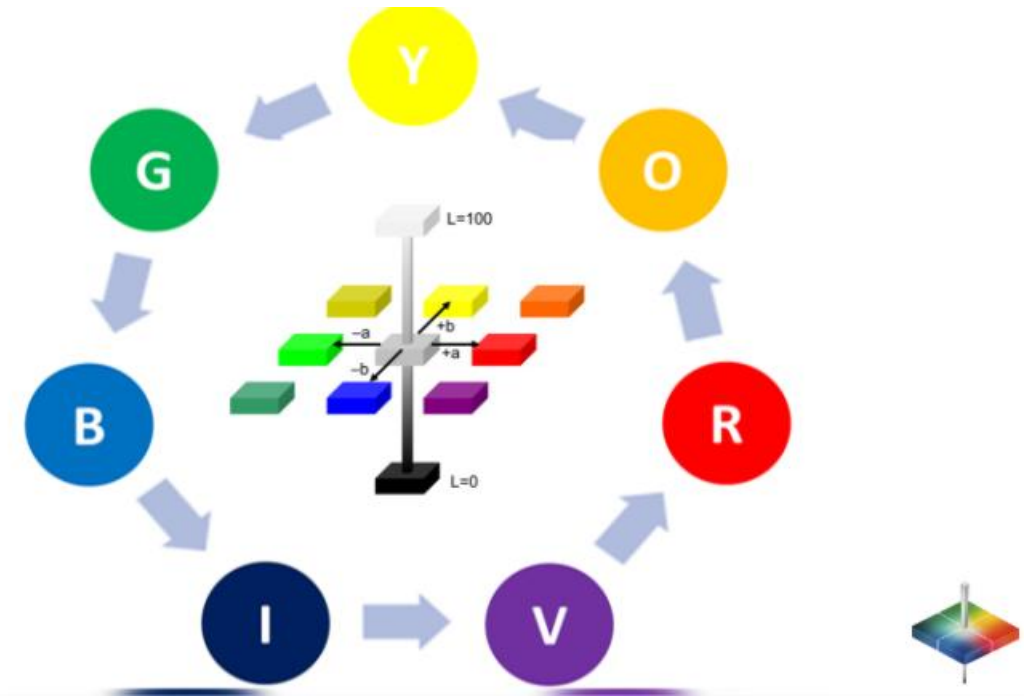
In this system, the **a** axis represents the red to green opponent pairs, The **b** axis represents the yellow to blue opponent pairs, and the **L** axis represents black to white opponent pairs.



Color Scales and Color Differences



We can also now recognize how the a to b chromatic plane of the L,a,b color space is arranged in a circular pattern, roughly following the color dispersion first discovered by Sir Isaac Newton - red, orange, yellow, green, blue, indigo and violet.





To bring it all together, L,a,b color scales closely align with human visual perception, firmly rooted in the foundational science that began with Sir Isaac Newton's discovery, and have evolved through our understanding of the physics, chemistry, and biology of how we see color, bringing us to today where we can now accurately measure and communicate color precisely and objectively using color spectrophotometry.



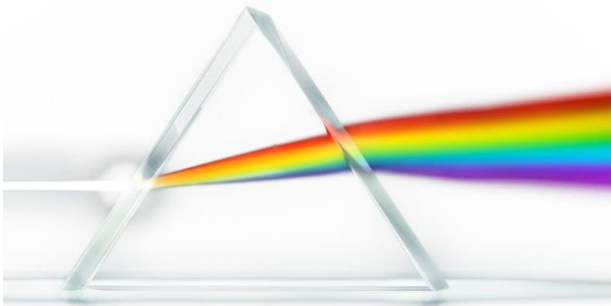
Fundamentals of Color and Appearance

Module 7:

Color Scales and Color Differences



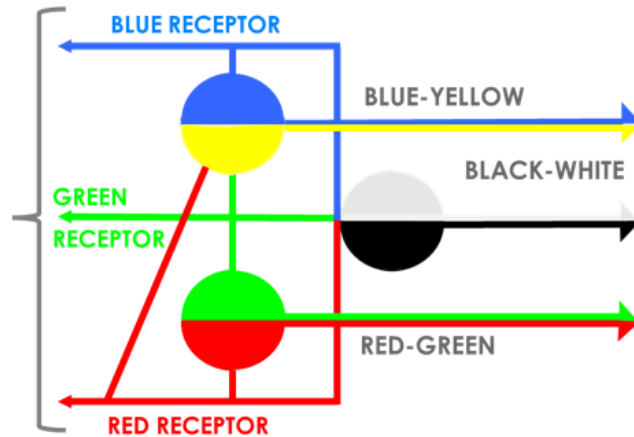
Dispersion



ROY-G-BIV

Red, Orange, Green, Blue,
Indigo, Violet

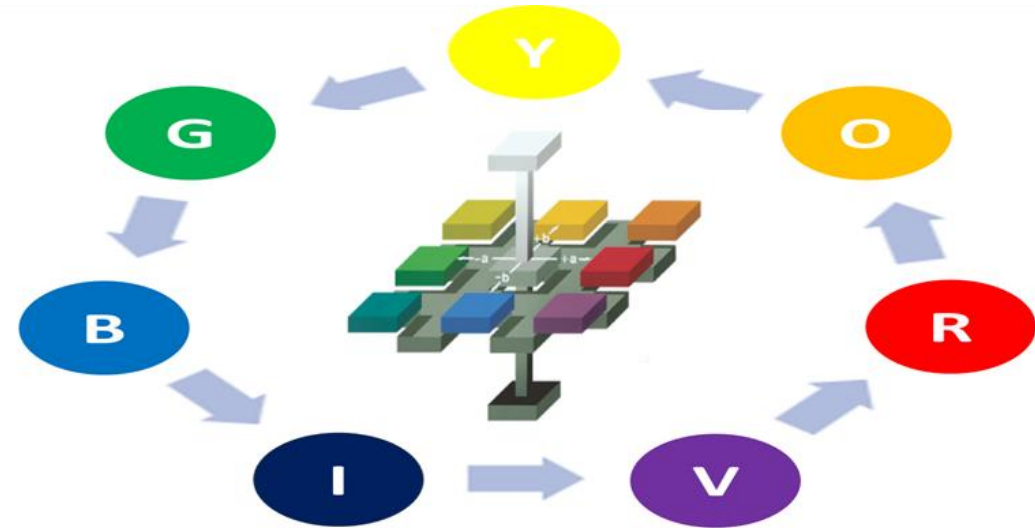
Opponent- Color Theory



Opponent Pairs

Red vs. Green
Blue vs. Yellow
Black vs. White

L, a, b Color Space



L, a, b

Red vs. Green
Blue vs. Yellow
Black vs. White

ROY-G-BIV

Red, Orange,
Yellow Green, Blue,
Indigo, Violet

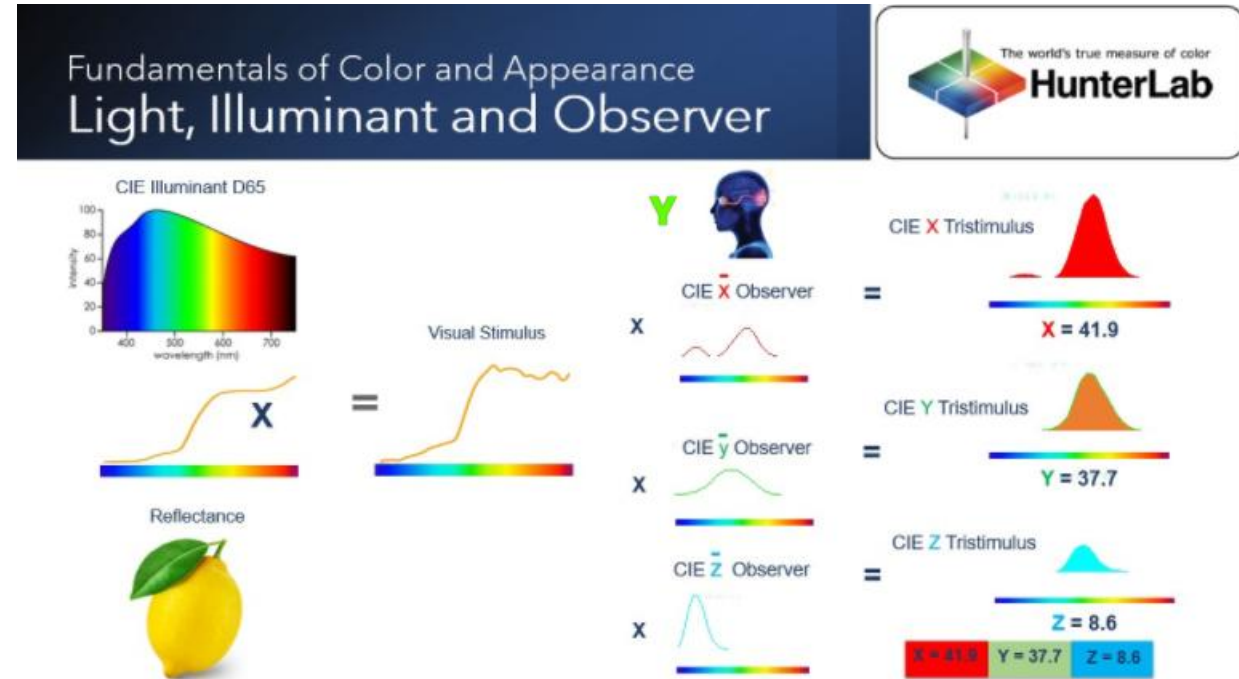
Fundamentals of Color and Appearance

Module 7:

Color Scales and Color Differences



In module 6 we learned about **CIE X,Y,Z Tristimulus Values**. While foundational to modern color science, its values X, Y, and Z, are not intuitive for visual interpretation or practical communication. To better align with how humans perceive color and to simplify color comparison and communication, color scales derived from these X Y Z color values were developed.

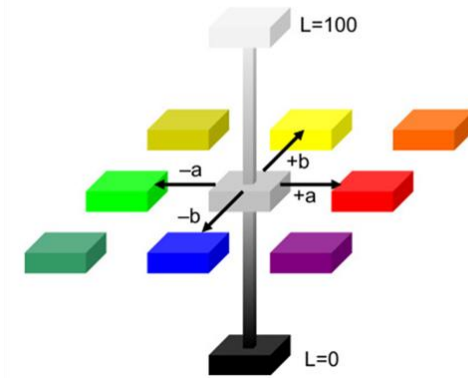


Color Scales and Color Differences

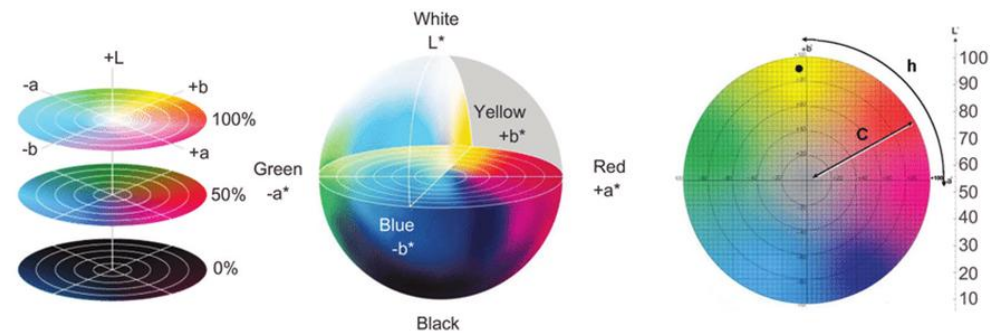


These scales, such as L, a, b and L, C, h , are more visually uniform and allow us to quantify and express color differences in ways that are both meaningful and practical for industrial and quality control applications and are now widely used across industries to ensure consistent, objective, and reproducible color evaluation.

L^*, a^*, b^* Color Space



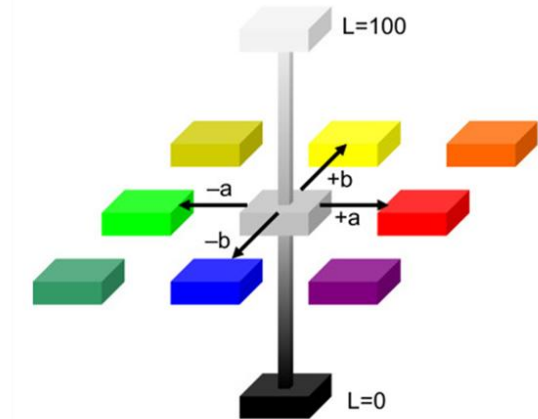
L^*, C^*, h^* Color Space



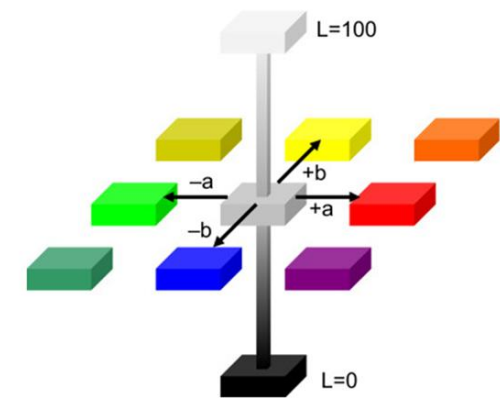
Color Scales and Color Differences



In earlier modules, we explored the two primary L, a, b, color models used today. Hunter L, a, b, invented by Richard Hunter and first introduced in 1942, and CIELAB which built on Hunter L, a, b and introduced in 1976. Both systems are derived from CIE X, Y, Z tristimulus color values first introduced in 1931, and both are grounded in the Opponent Color Theory.



Hunter L, a, b (1942)



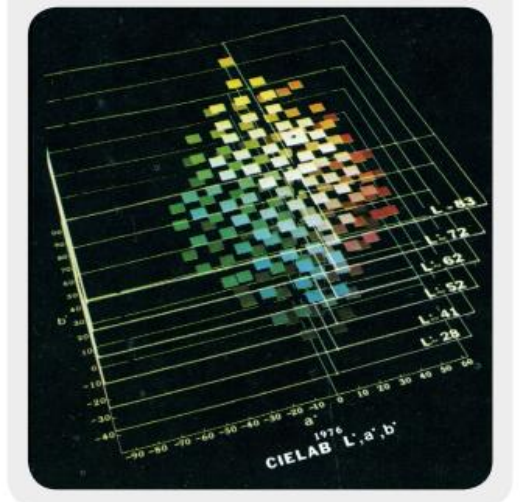
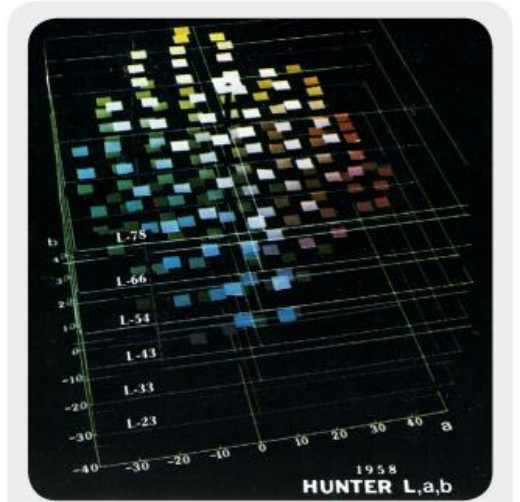
CIE L*, a*, b* (1976)

Color Scales and Color Differences



Hunter L, a, b and CIE L*,a*,b* scales are both mathematically derived from CIE X, Y, Z values, however, neither scale is visually uniform.

- Hunter L, a, b is over expanded in the blue region of color space.
- CIE L*,a*,b* is over expanded in the yellow region.



Color Scales and Color Differences

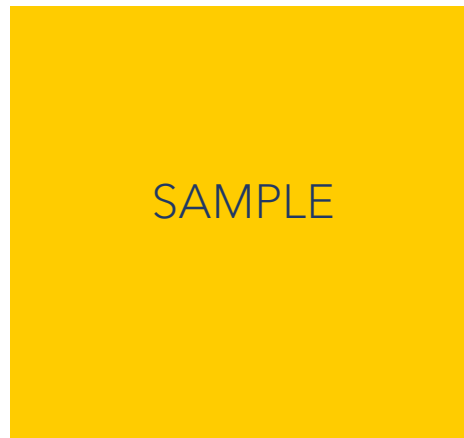


Because of these differences, color measurement values using one model will not numerically match those from the other when measuring the same sample due to their underlying math as seen in this example.

Our sample shows that the CIE L, a, and b values are vastly different from the Hunter L, a, and b values.

Hunter L, a, b (1942)

$$\begin{aligned}L &= 61.42 \\a &= + 18.11 \\b &= + 32.23\end{aligned}$$



CIE L*,a*,b* (1976)

$$\begin{aligned}L^* &= 67.81 \\a^* &= + 19.56 \\b^* &= + 58.16\end{aligned}$$

Color Scales and Color Differences



Understanding which color scale should be used, and why, is essential for accurate and consistent color evaluation of your products. It is equally important to ensure that the same color scales are used consistently across products, instruments, and locations, for meaningful comparison of results across different applications and teams.

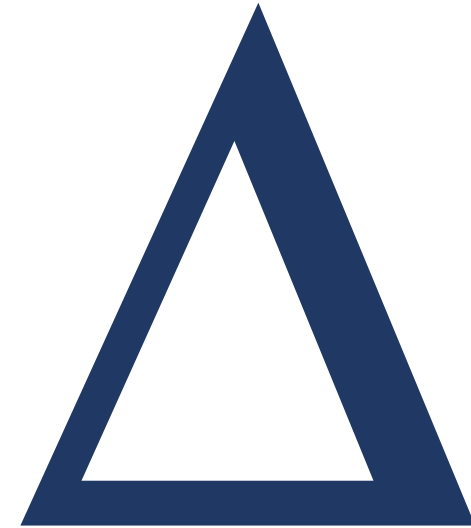




Color differences are always determined using the formula:

Sample minus Standard

This calculation tells us how much a sample's color deviates from the target - or reference standard - and in which direction.

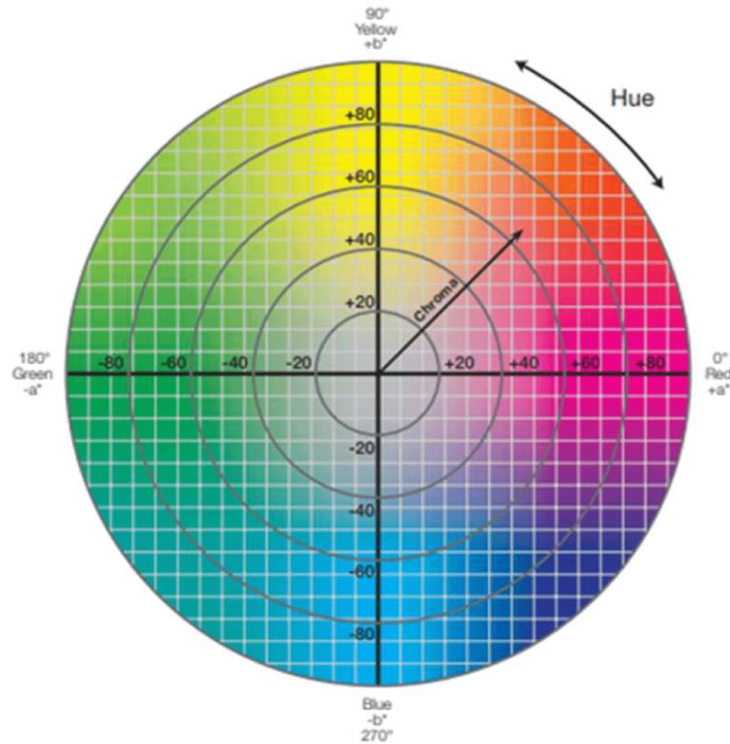


DELTA
(Difference)

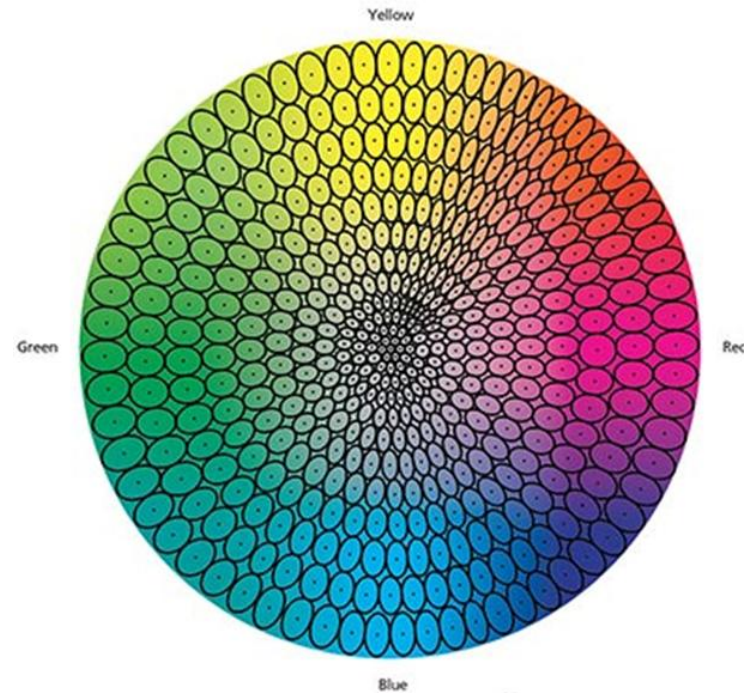
Color Scales and Color Differences



There are two primary ways to express this difference: DE, or rectangular tolerancing, and DEcmc, or ellipsoid tolerancing:



DE rectangular tolerancing





DEcmc ellipsoid tolerancing



Rectangular tolerancing treats color variation equally across all three L, a, and b asymmetric axis.

- If **delta L** is positive, the sample is lighter than the standard. If negative, it would be darker than the standard
- If **delta a** is positive, the sample is redder, or less green, than the standard. If negative; it would be greener (or less red) than the standard.
- If **delta b** is positive, the sample is more yellow, or less blue, than the standard. If negative, it would be bluer, or less yellow.

	—		=	COLOR DIFFERENCES
L* = 71.9		L* = 69.7		$\Delta L^* = +2.2$
a* = +10.2	—	a* = +12.7	=	$\Delta a^* = -2.5$
b* = +58.1		b* = +60.5		$\Delta b^* = -2.4$

In this example, the differences in delta L, delta a, and delta b show that the yellow sample is lighter, greener, and bluer than the standard.



We can also calculate total color difference symmetrically as **delta E (ΔE)**. This single number represents total color difference in 3-dimensional color space, calculated as the square root of the sum of squared delta L, delta a, and delta b values.

The smaller the **ΔE value**, the closer the match. This combines the three components into one value, giving us a quick and comprehensive measure of how far the sample color is from the standard.

ΔE

Color Scales and Color Differences

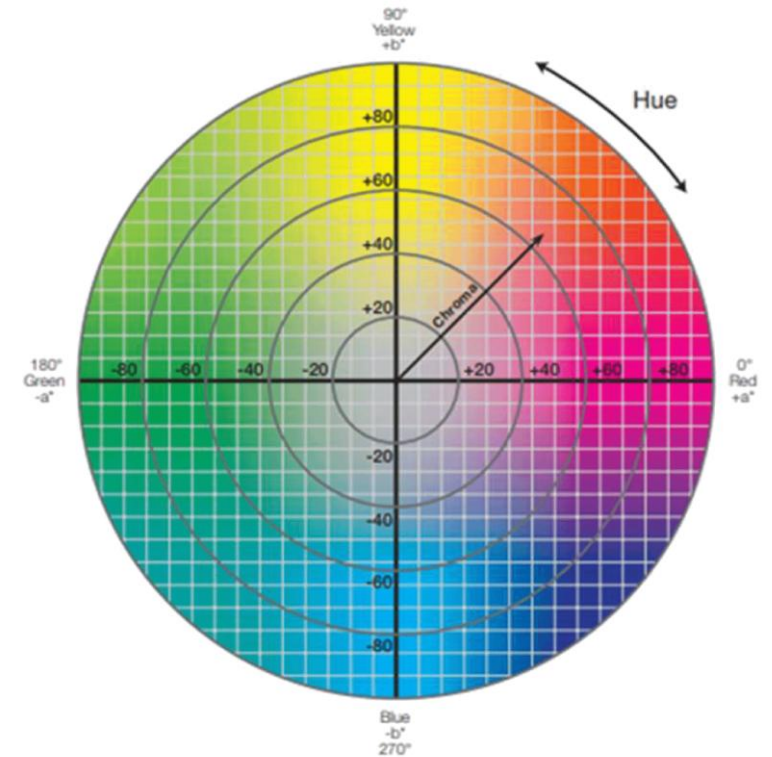


The original ΔE^* formula is a Euclidean distance in 3D color space. It involves squaring the differences in L^* , a^* , and b^* , summing them, and taking the square root – not a cube.

$$\Delta E_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

Delta E tolerancing is simple to compute and widely used, but it doesn't account for how the human eye perceives color differences.

As a result, it may overestimate or underestimate differences in certain regions of color space.



DE rectangular tolerancing

Color Scales and Color Differences

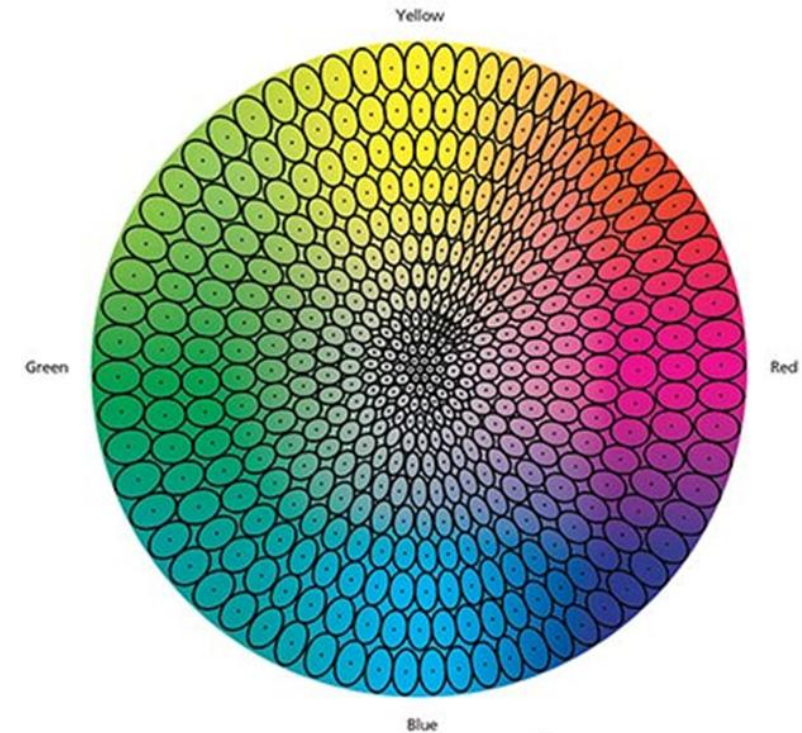


To address the limitations of rectangular color tolerancing, ΔE_{cmc} was developed. ΔE_{cmc} is a tolerance-based metric, not a pure distance. It reshapes the equal ΔE sphere into an ellipsoid based on perceptual sensitivity to lightness, chroma, and hue. The formula is:

$$\Delta E_{CMC(l:c)} = \sqrt{\left(\frac{\Delta L^*}{lS_L}\right)^2 + \left(\frac{\Delta C^*}{cS_C}\right)^2 + \left(\frac{\Delta H^*}{S_H}\right)^2}$$

Where: S_L, S_C, S_H are scaling (weighting) functions that adjust for how the human eye perceives changes in lightness, chroma, and hue.

l and c are user-set parameters (commonly $l : c = 2 : 1$ for acceptability, $1 : 1$ for perceptibility).



ΔE_{cmc} ellipsoid tolerancing

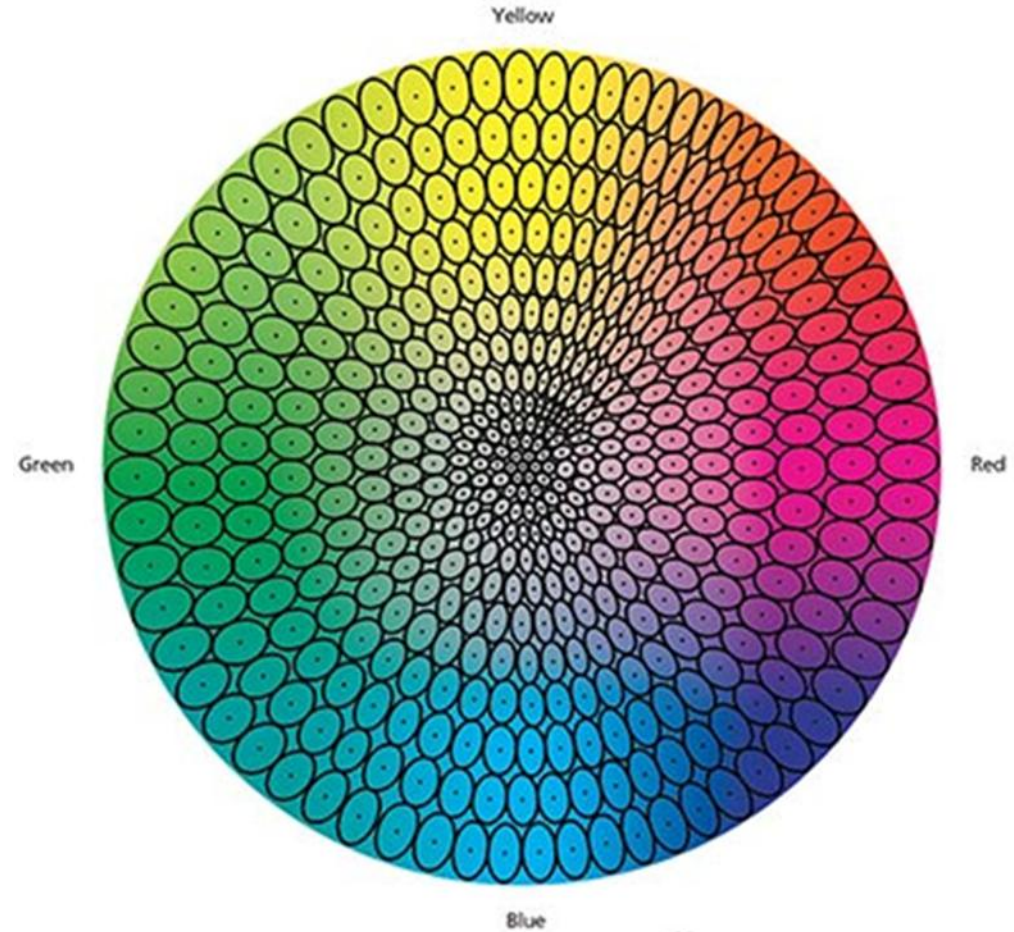
Color Scales and Color Differences



For example, in the orange region, the ellipsoids are narrower, indicating tighter tolerance. In the green region, they widen, reflecting the eye's reduced sensitivity to shifts in that area.

Additionally, ellipsoids in high-chroma regions, where colors are vivid, are larger than those in low-chroma areas, where colors are more muted.

This adaptive approach allows DEcmc to better reflect human visual sensitivity and is widely used in industries where precise color matching is critical, such as food, textiles, coatings, and plastics manufacturing.



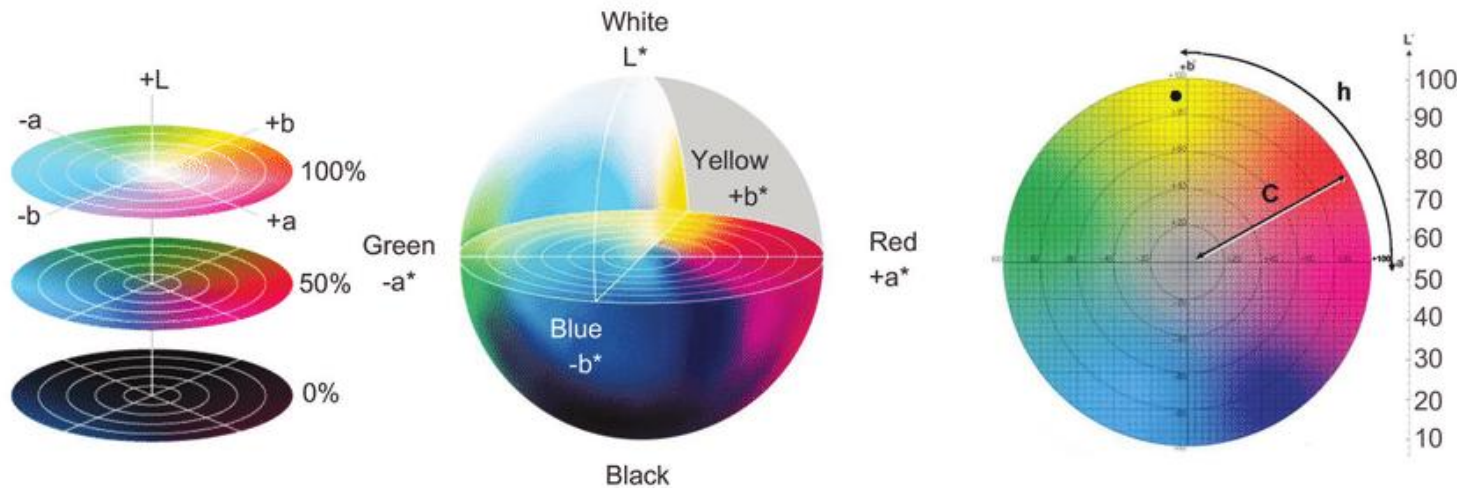
DEcmc ellipsoid tolerancing

Color Scales and Color Differences



Another way to express color is the L,C,h model. It uses cylindrical coordinates, where L is lightness, C is chroma, or color intensity, and h is hue angle.

L,C,h values help quantify how colors differ in lightness, chroma, and hue. While L, a, b provides precise numerical positioning and delta E calculations, L, C, h is a more intuitive description of color attributes for nontechnical audiences.



L*, C*, h* Color Space



Let's apply what we have learned to determine appropriate color tolerances for your products.

Most people can perceive color differences as small as 1 delta unit.

However, what qualifies as an acceptable color difference depends heavily on the application.





In automotive paint, tolerances are extremely tight because adjacent panels must match perfectly. Even minor mismatches are noticeable, so only the minimum perceptible difference is tolerated.





In contrast, snack food production like these potato chips allow for broader color variation, since consumers expect some inconsistency, so maximum acceptable differences are defined to ensure visual appeal without requiring perfect uniformity.



Color Scales and Color Differences



Understanding the difference between **minimum perceptible** and **maximum acceptable** thresholds is essential for setting effective and application-specific quality tolerances.

- What is acceptable for color matching of automotive paint is close to being a **minimum perceptible limit**.
- What is acceptable for snack foods is greater and the **maximum acceptable limit** defines the tolerance for the product.

Maximum Acceptable



Minimum Perceptible



Color Scales and Color Differences



While we have explained the various scales, color difference methods, and calculations used to establish color standards and tolerances, it is important to recognize that these are preconfigured and easily selectable within the spectrophotometer's software. Users are not required to perform manual calculations, as the instrument automates these processes to ensure accuracy and efficiency.

Name	Date	Time	400nm	410nm	420nm	430nm	440nm	450nm	460nm
Sample 163	9/25/2024	3:13:29 PM	81.02	79.93	82.02	83.76	85.12	85.89	86.02
Sample 162	9/25/2024	3:13:26 PM	81.00	79.87	81.96	83.75	85.10	85.88	86.02
Sample 161	9/25/2024	3:13:23 PM	80.97	79.83	81.94	83.77	85.10	85.85	86.02
Sample 160	9/25/2024	3:13:19 PM	81.04	79.99	82.05	83.78	85.16	85.91	86.02
Sample 159	9/25/2024	3:13:16 PM	81.04	79.95	82.04	83.79	85.15	85.92	86.02
Sample 158	9/25/2024	3:13:13 PM	81.03	79.95	82.04	83.78	85.13	85.92	86.02
Sample 157	9/25/2024	3:13:10 PM	80.99	79.84	81.93	83.73	85.07	85.85	86.02
Sample 156	9/25/2024	3:13:07 PM	81.01	79.96	82.04	83.79	85.13	85.88	86.02
Sample 155	9/25/2024	3:13:03 PM	80.99	79.87	81.97	83.76	85.09	85.87	86.02

Job 9/13/2024 2:27:38 PM Standardize 1" Port Workspace Test

Fundamentals of Color and Appearance

Module 7:

Color Scales and Color Differences



Thank you for joining us on this journey through color science.

Be sure to watch module 8 in this Fundamentals of Color and Appearance series, **Instrument Geometry**, where we will learn the differences between diffuse and directional geometries, how they are designed, how they function, and their intended applications.

And be sure to visit hunterlab.com to learn more about how our solutions can help you achieve color confidence, every time, or to schedule a consultation with one of our color experts.

Fundamentals of Color and Appearance

Module 8

Instrument Geometry

Color Science Educational Series



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