Perception: Psychophysics and Modeling

15 | Colour Vision II

Felix Wichmann

Neural Information Processing Group
Eberhard Karls Universität Tübingen

Additional reading

Hurvich, L. M., & Jameson, D. (1957). An opponent-process theory of color vision. *Psychological Review,* 64(6), 384–404.

Krauskopf, J., Williams, D. R., & Heeley, D. W. (1982). Cardinal directions of color space. *Vision Research*, 22, 1123–1131.

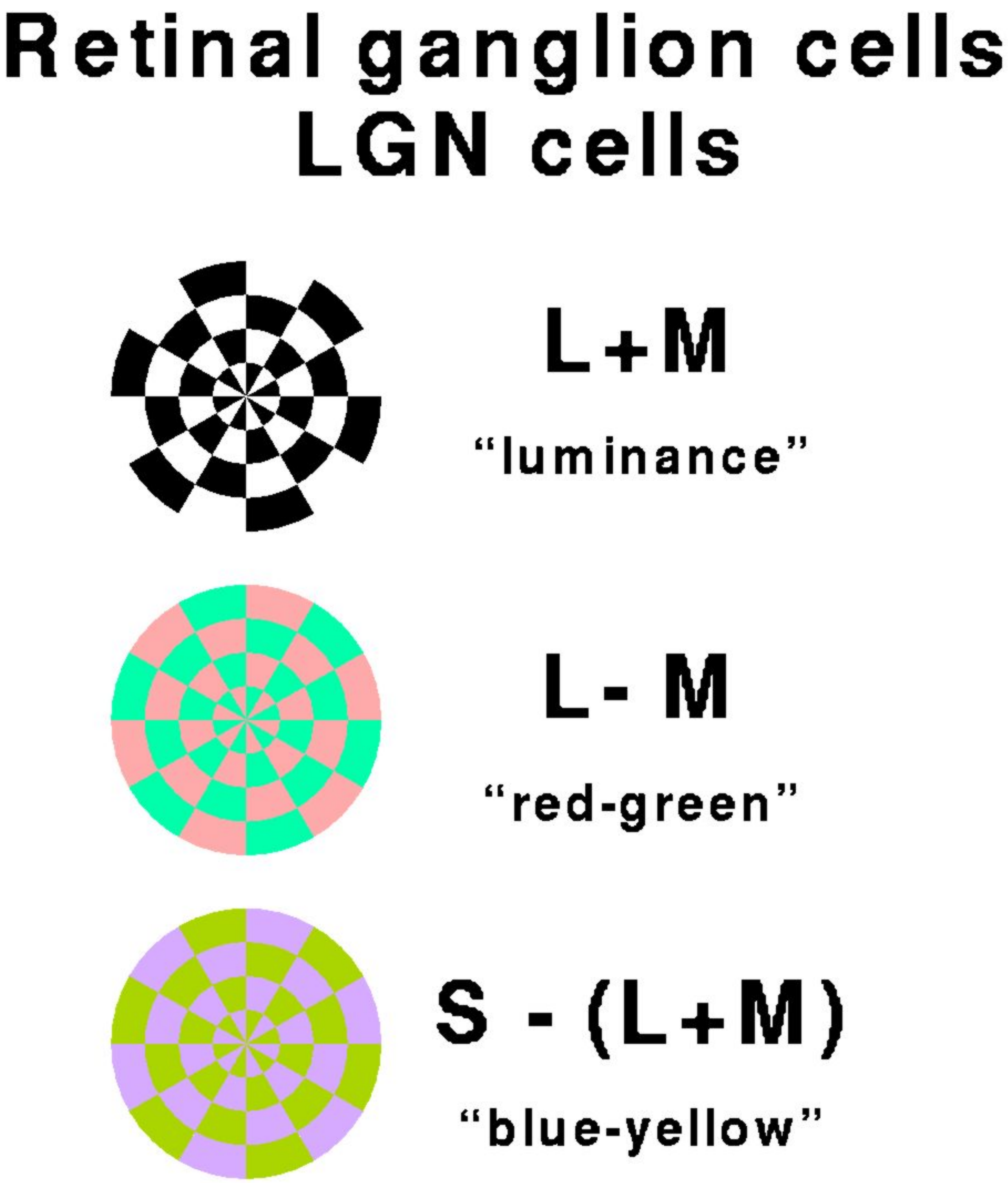
Wallisch, P. (2017). Illumination assumptions account for individual differences in the perceptual interpretation of a profoundly ambiguous stimulus in the color domain: "The dress." *Journal of Vision*, 17(4), 5.

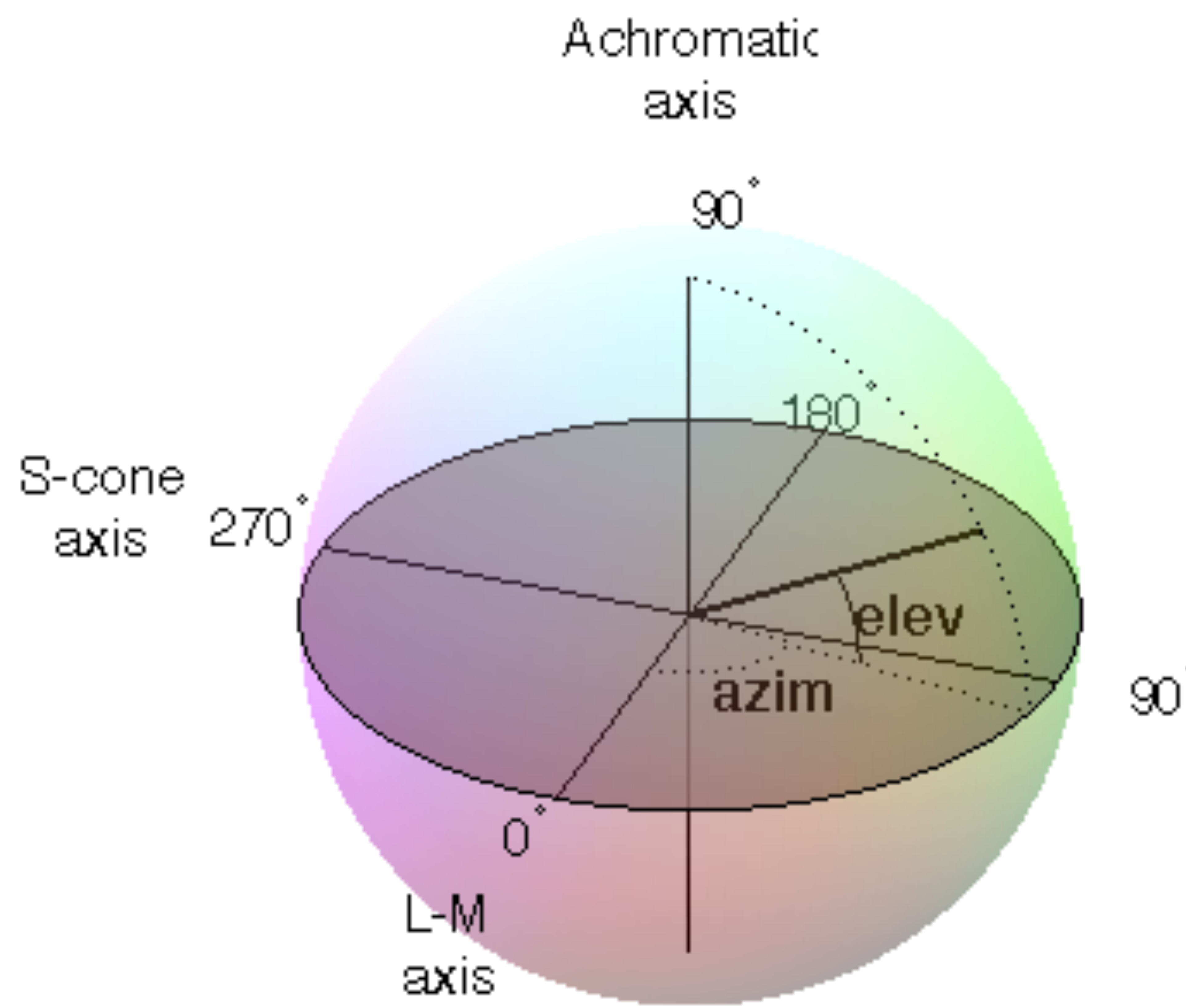
Witzel, C., Racey, C., & O'Regan, J. K. (2017). The most reasonable explanation of "the dress": Implicit assumptions about illumination. *Journal of Vision*, 17(2), 1.

Perception of Colour (VL15, today)

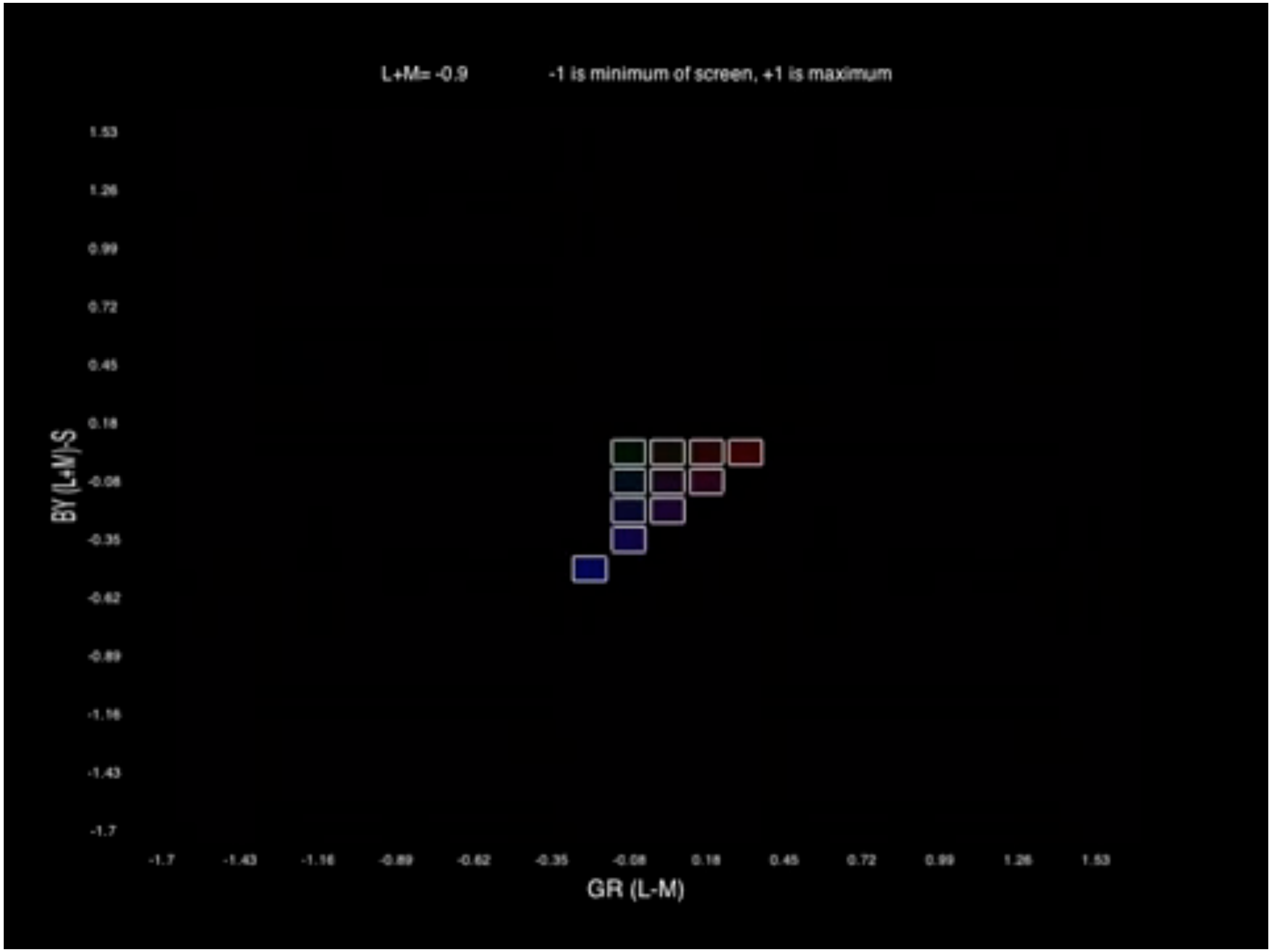
- Colour is purely psychological—the world and physics does not know colours!
- Spectral power distribution (light) and spectral or surface reflectance functions
- Basic Principles of Colour Perception
  - Step 1: Colour Detection
  - Step 2: Colour Discrimination
  - **Step 3: Colour Appearance (VL15)**
- **Individual Differences in Colour Perception (VL15)**
- **From the Colour of Lights to a World of Colour (VL15)**
- **What Is Colour Vision Good For? (VL15)**

Cone-opponent colour space (DKL space)





Cone-opponent colour space (DKL space)

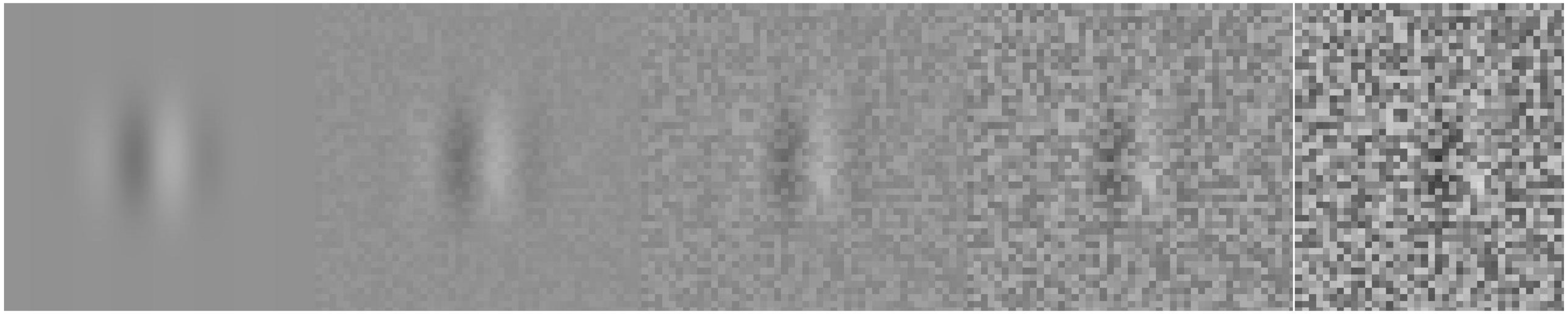


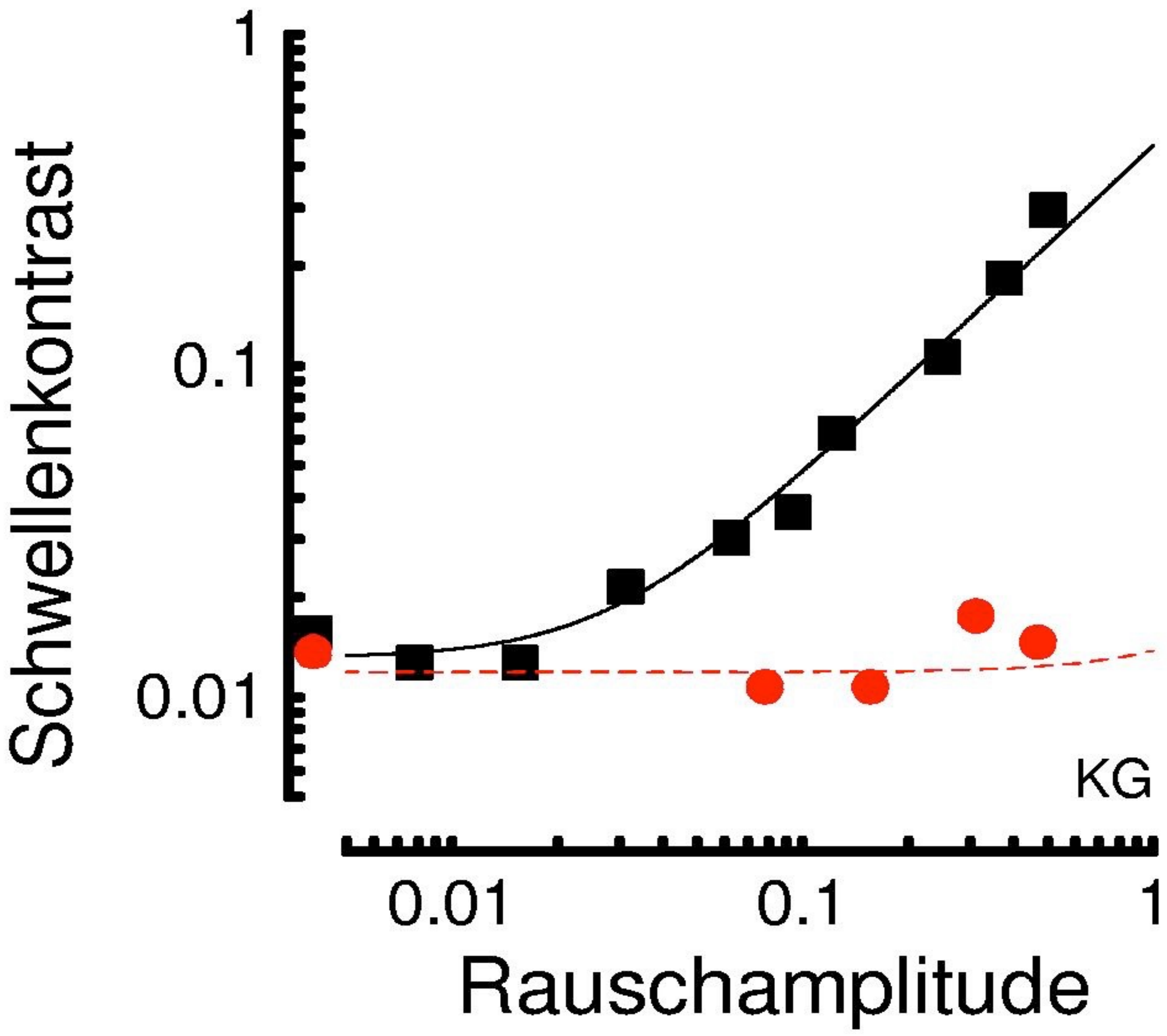
Ascent Through DKL-space, by Alex Holcombe.

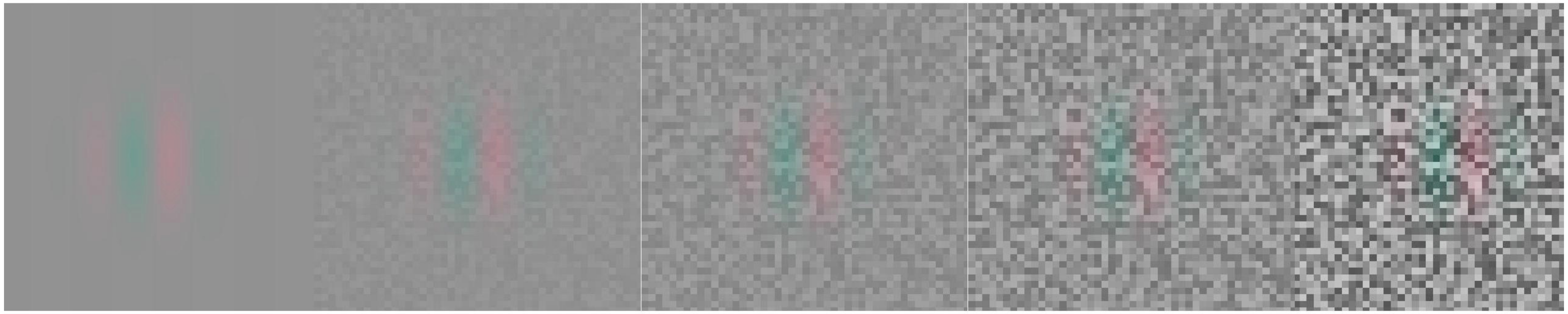
https://alexholcombe.wordpress.com/2011/07/11/color-space-pictured-and-animated-derrington-krauskopf-lennie/

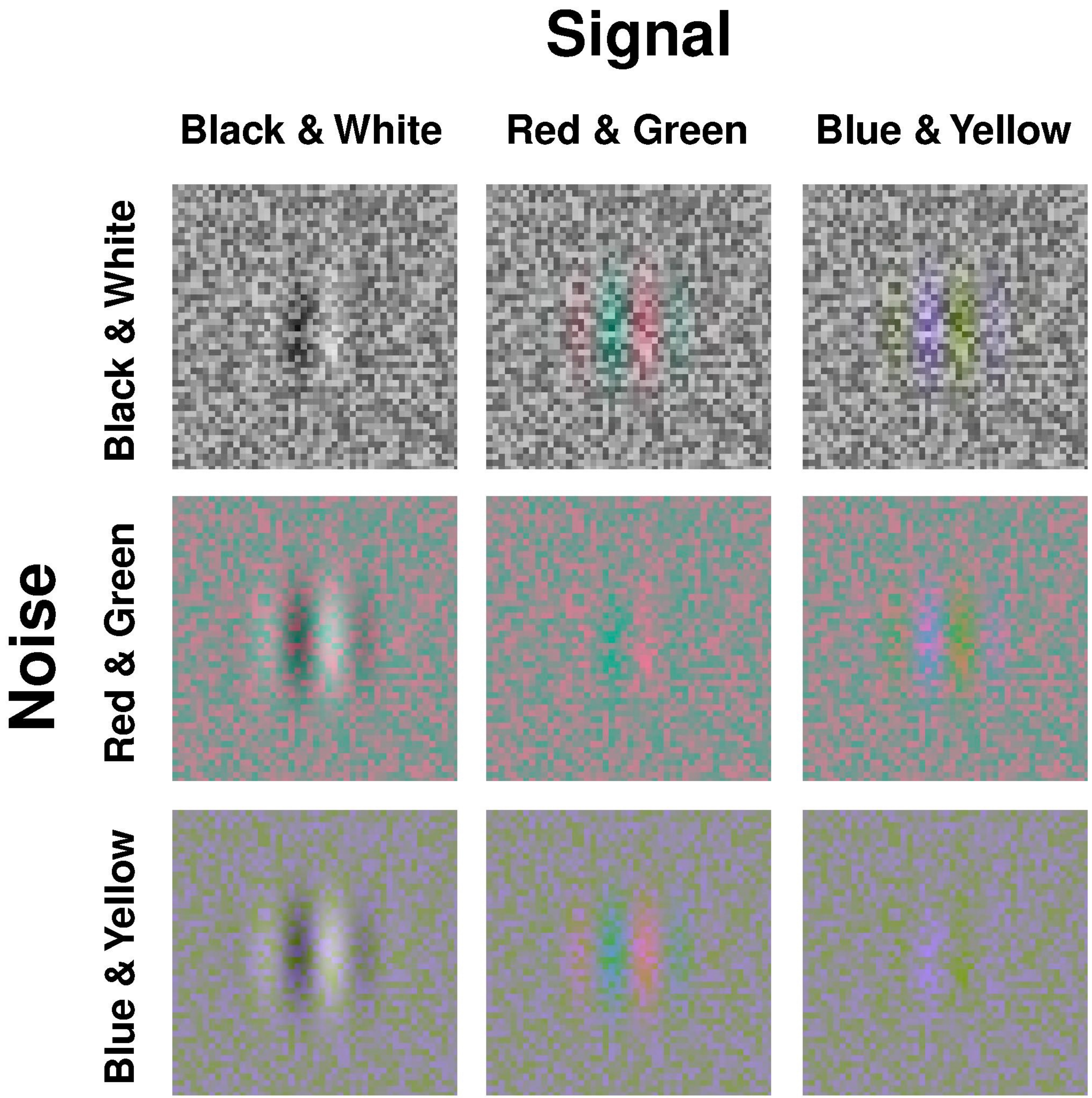
Are the opponent channels really independent?

Opponent Colours: Independence Assessed by Masking



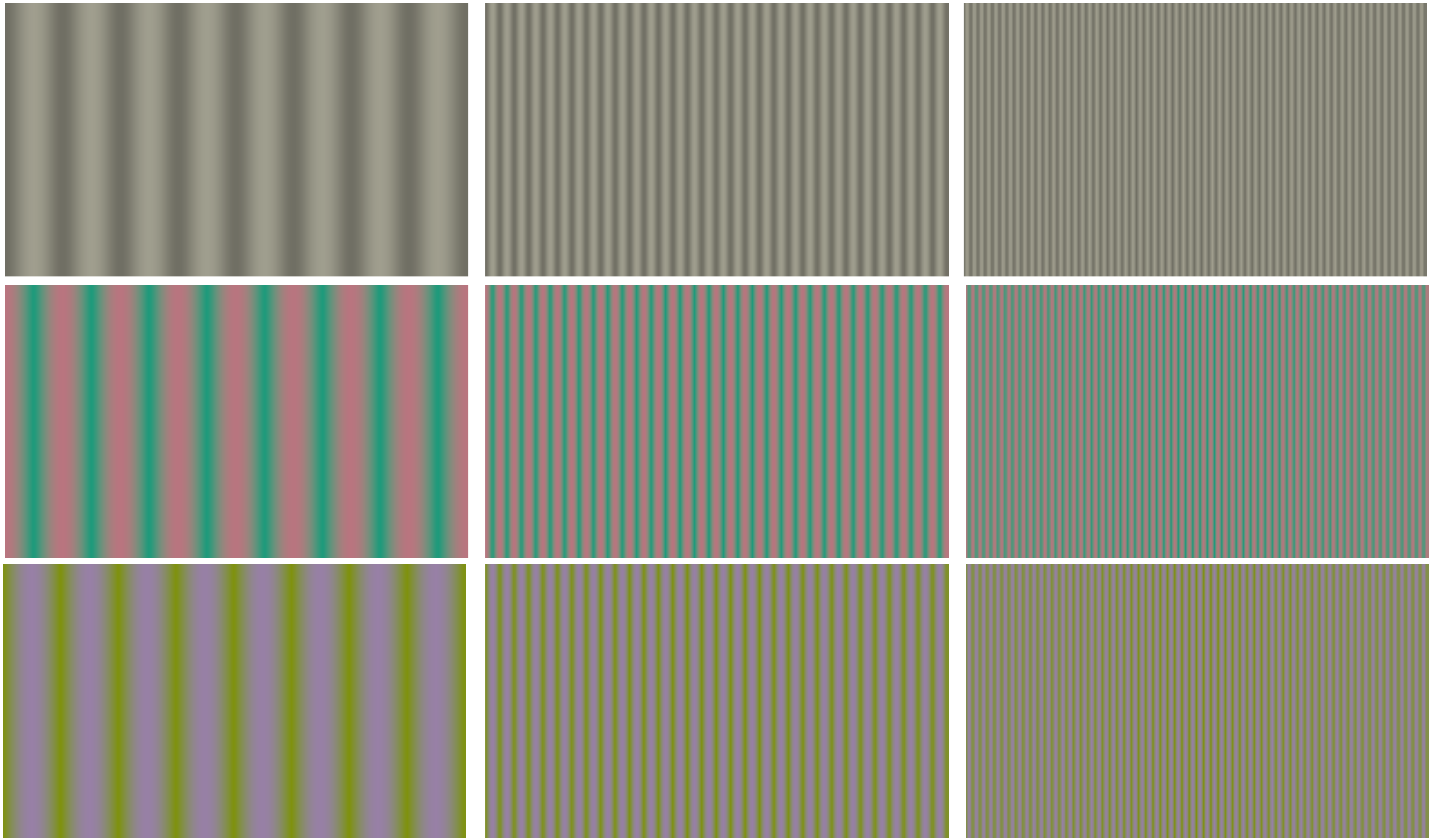




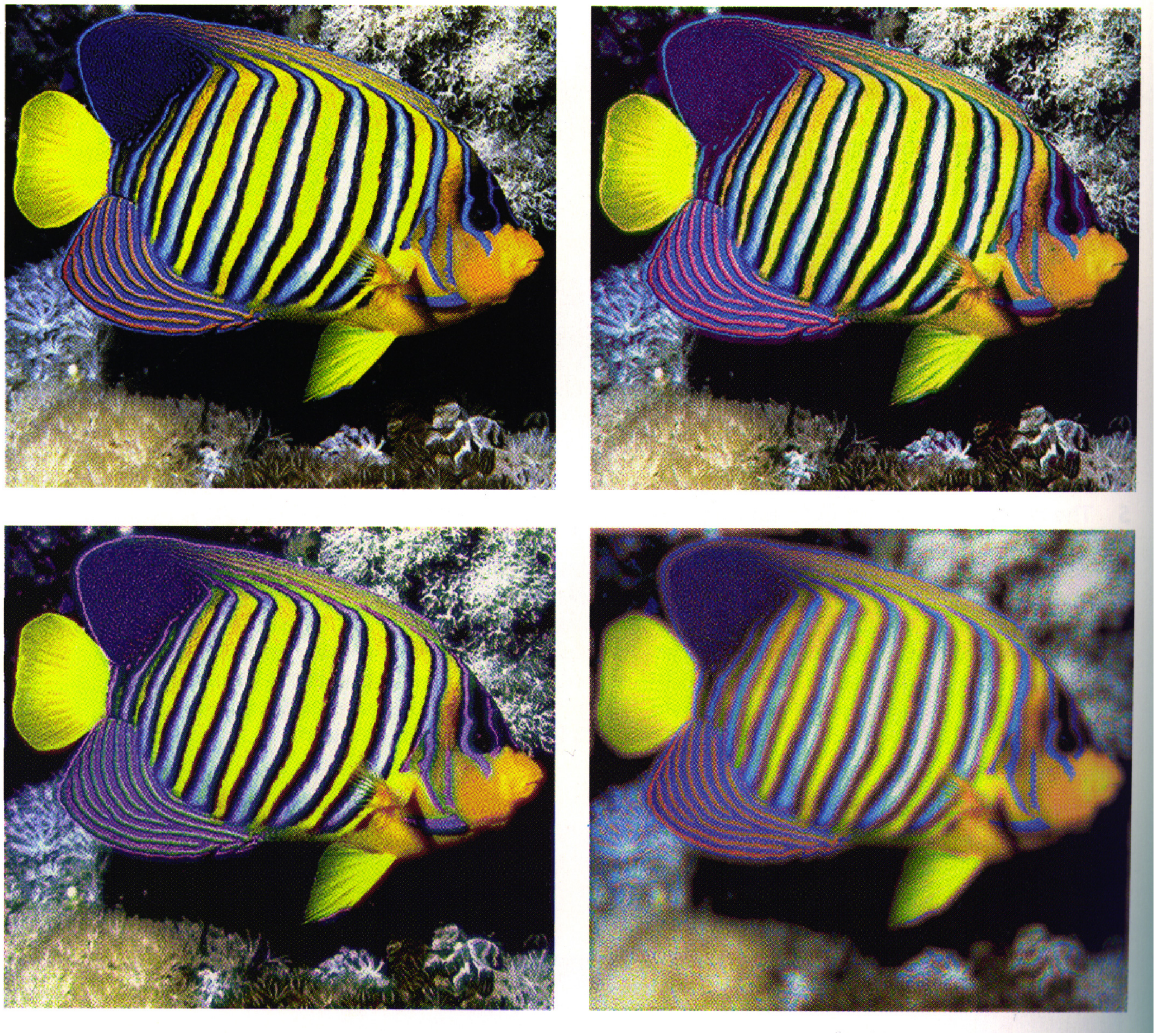


Signal
Black & White
Red & Green
Blue & Yellow
Noise
Black & White
Red & Green
Blue & Yellow

Spatial frequency limits of the opponent channels



Colour and visual acuity



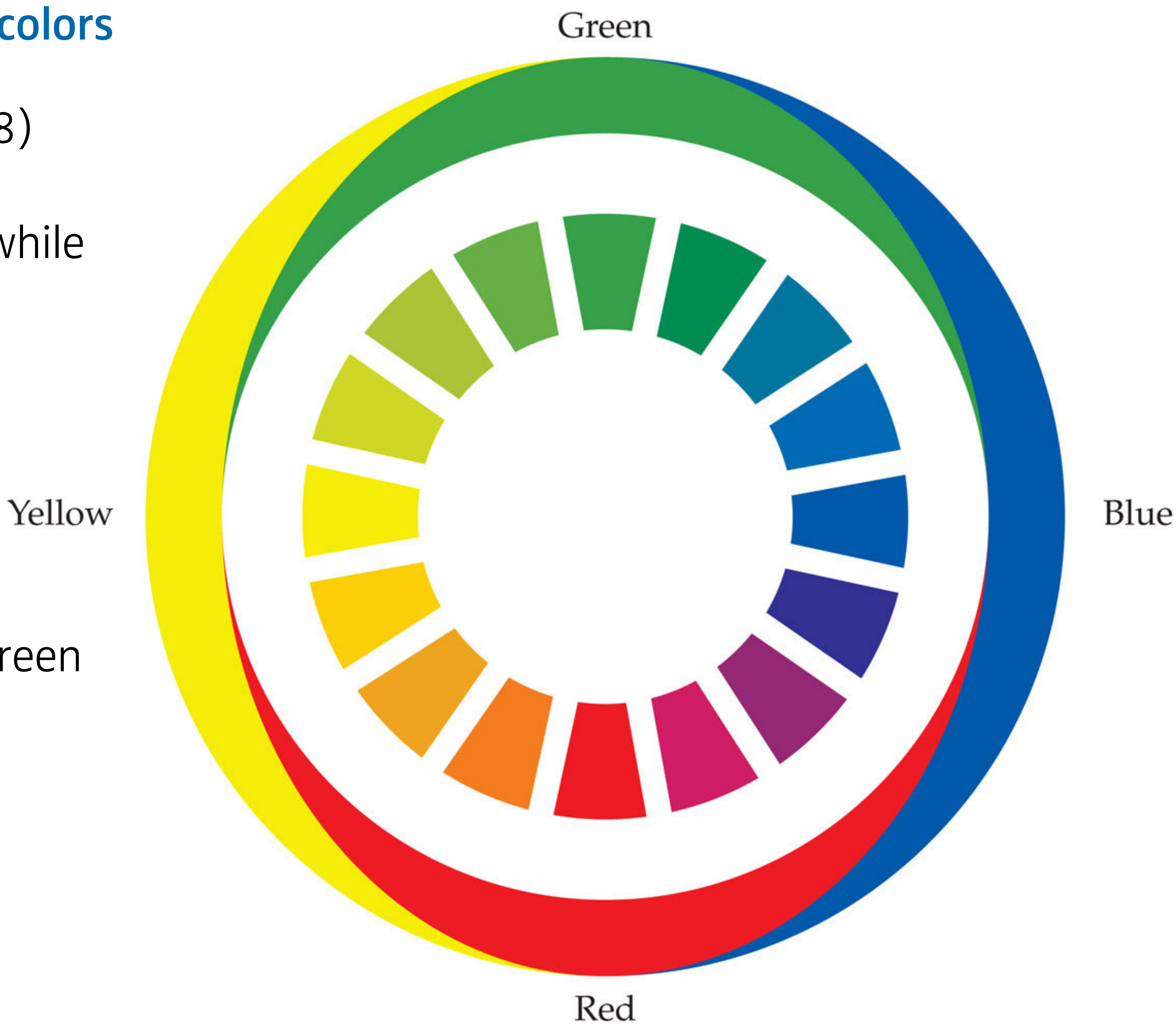
Linking cone opponency to colour appearance

Hering's idea of opponent colors

Ewald Hering (1834–1918) noticed that some color combinations are "legal" while others are "illegal."

We can have bluish green (cyan), reddish yellow (orange), or bluish red (purple).

We cannot have reddish green or bluish yellow.



SENSATION & PERCEPTION 4e, **Figure 5.14**

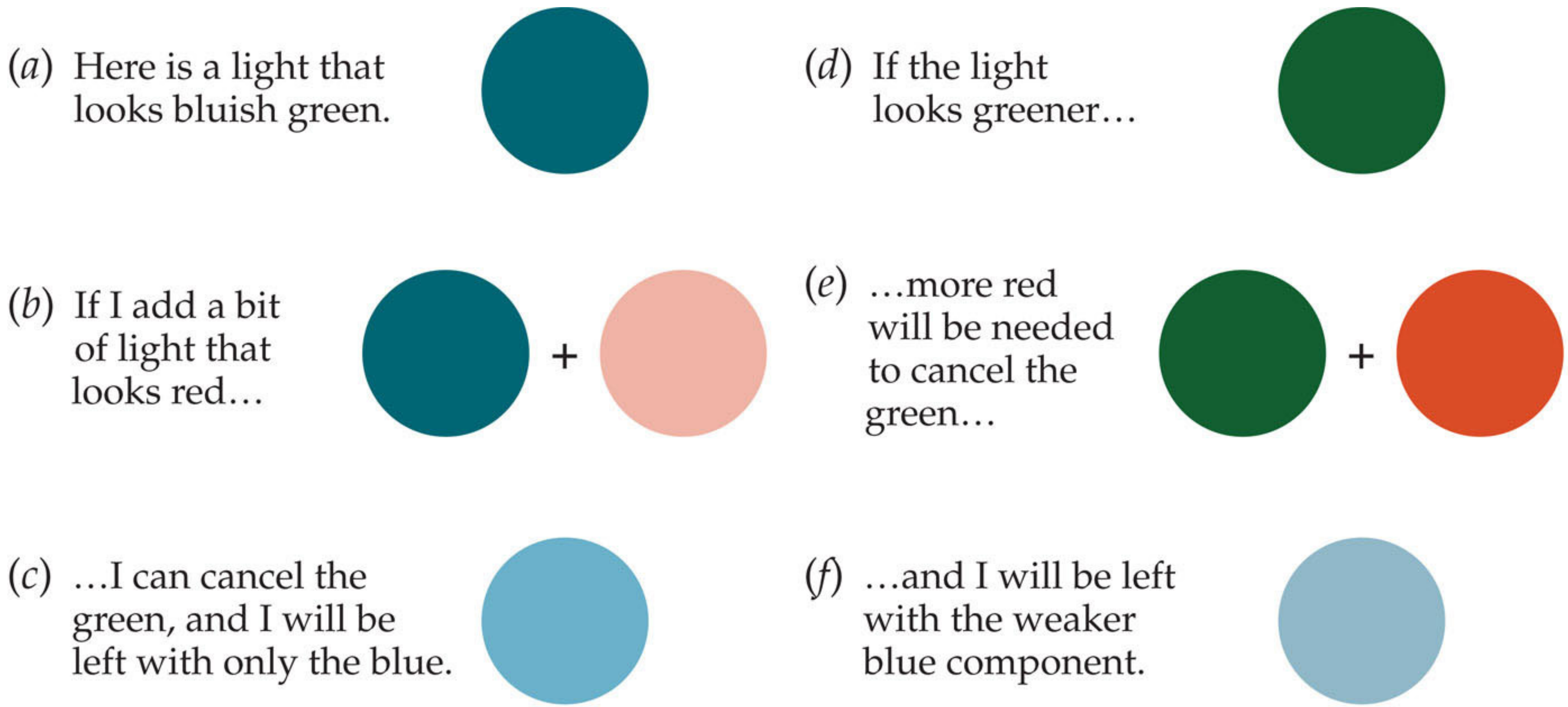
Opponent colour theory

The theory that perception of color depends on the output of three mechanisms, each of them based on an opponency between two colors: red–green, blue–yellow, and black–white.

Is there a way to quantify these opponent mechanisms?

Hue cancellation experiments (Hurvich & Jameson, 1957) to measure subjective colour appearance (different from discrimination thresholds)

A hue cancellation experiment



***SENSATION & PERCEPTION 4e,* Figure 5.15**

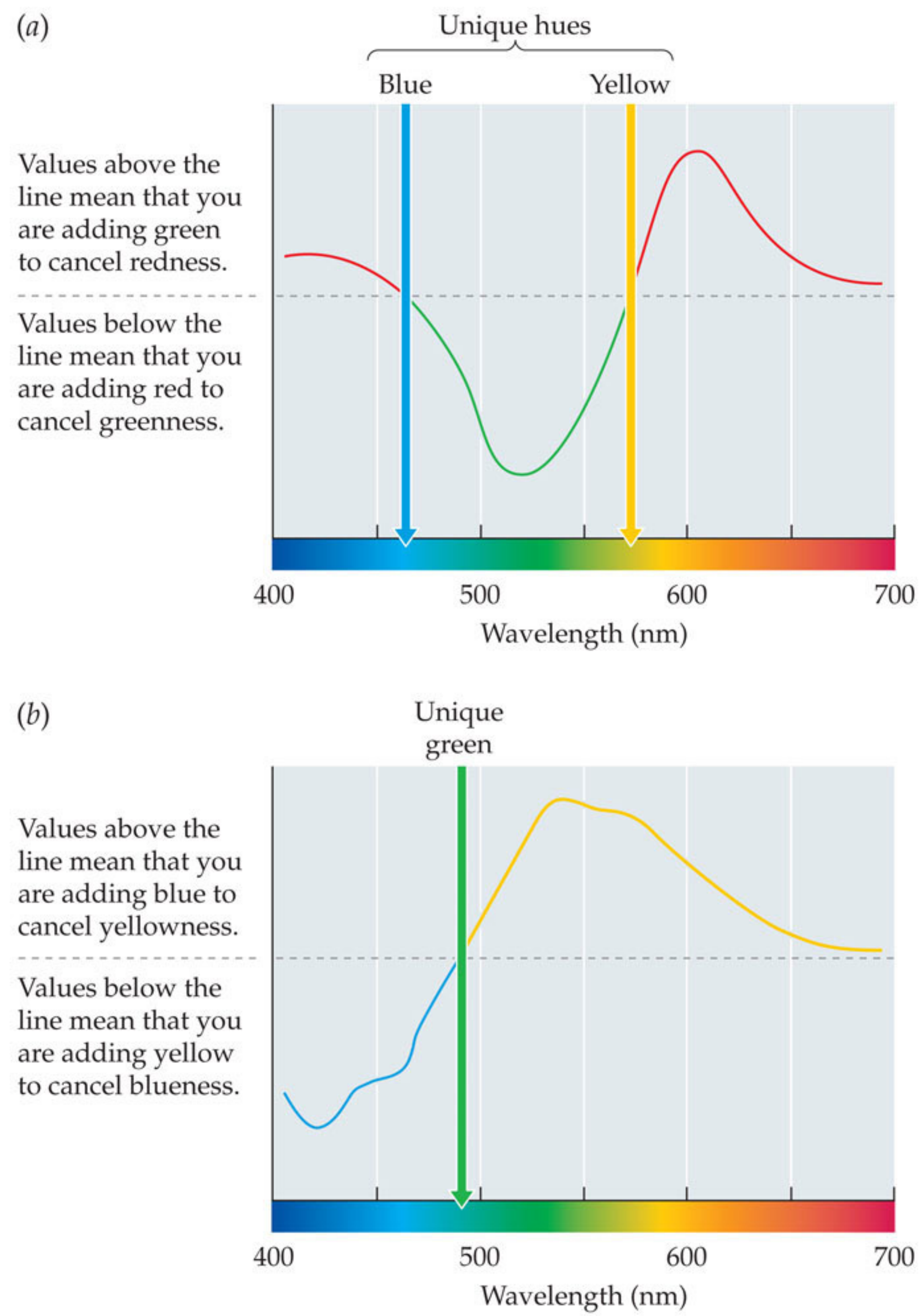
Results from a hue cancellation experiment

Starting at 400 nm, lights look reddish blue (violet). Could either add green to cancel redness (a) or add yellow to cancel blueness (b).

Moving along the spectrum results in different amounts of red / green and blue/yellow cancelling.

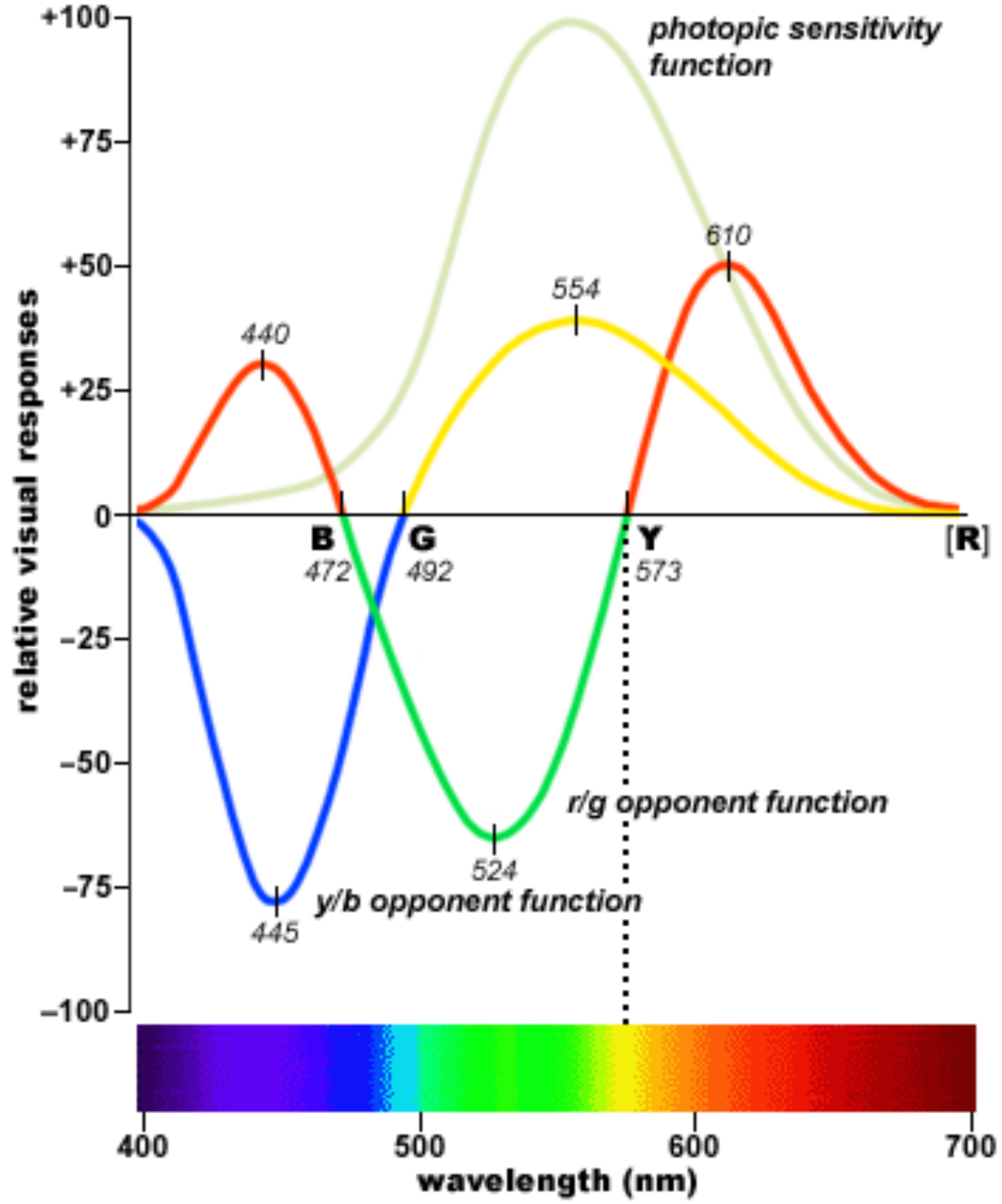
Unique hues: can be described by only a single colour term (blue, yellow, green, red). For example: unique blue has no hint of red or green.

Red doesn't have a spectral locus: all very long wavelengths look red. Red does not exist as a monochromatic light.



***SENSATION & PERCEPTION* 4e, Figure 5.16**

Colour opponent channels



Determining the wavelengths of unique hues

We can use the hue cancellation paradigm to determine the wavelengths of unique hues.

Individually, subjects are remarkably consistent in where in the visible spectrum they locate the unique hues. Some subjects can consistently identify spectral lights as unique within as small a range of 2 nanometres (nm), although the range does not generally exceed 10 nm (Webster et al, 2000).

Interpersonally however, variation in the location of the unique hues can be substantial. This is especially true of unique green. A study into the spectral location of unique green by Schefrin and Werner (1990), for instance, found that otherwise normal subjects (subjects who passed standard tests for colour blindness, such as the Ishihara test) located unique green anywhere between 488nm and 536nm. This is a range of 49nm, or around 16% of the visible spectrum.

Colour opponent axes vs cone opponent axes

Cardinal & unique axes only partially agree!

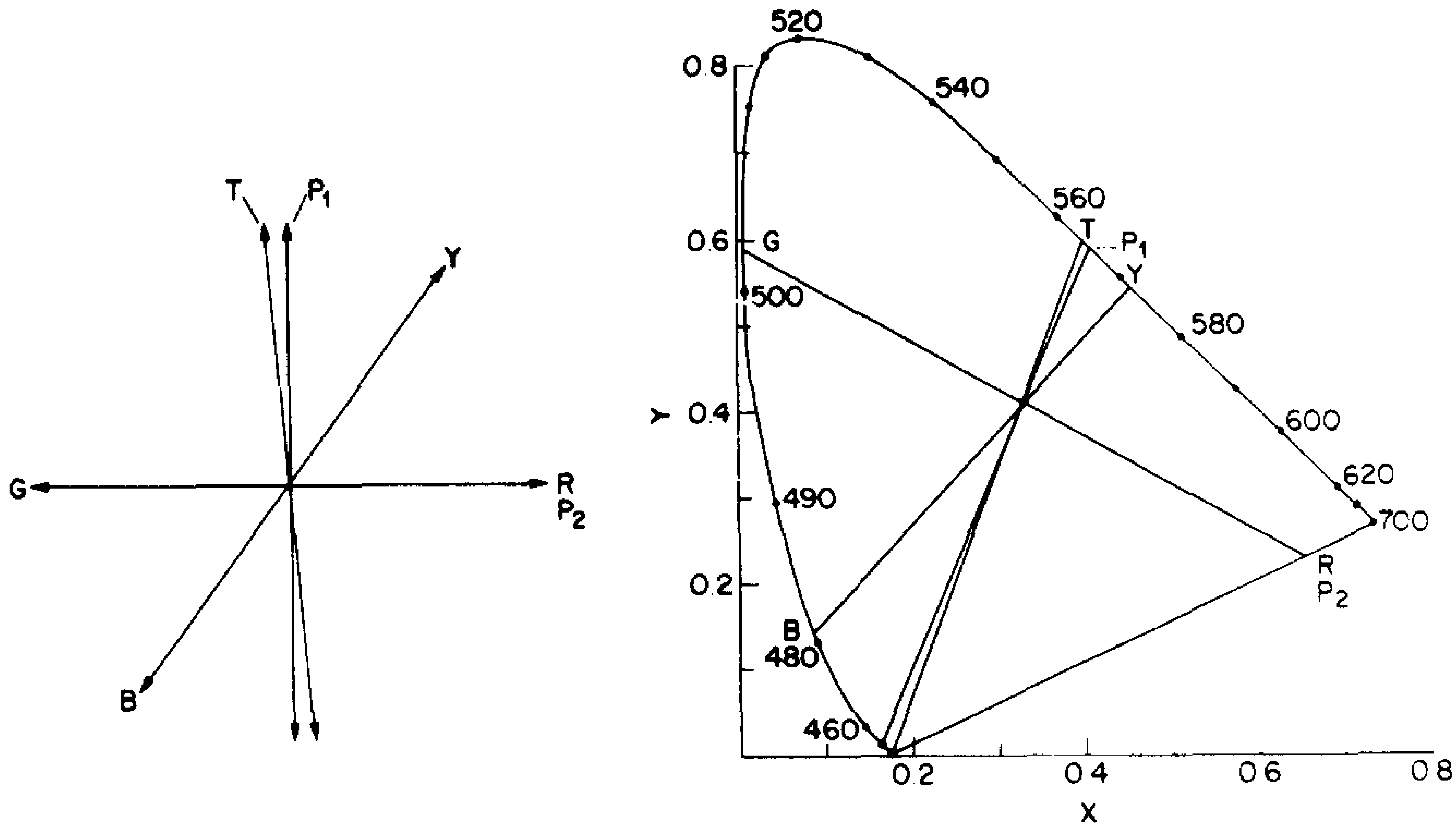
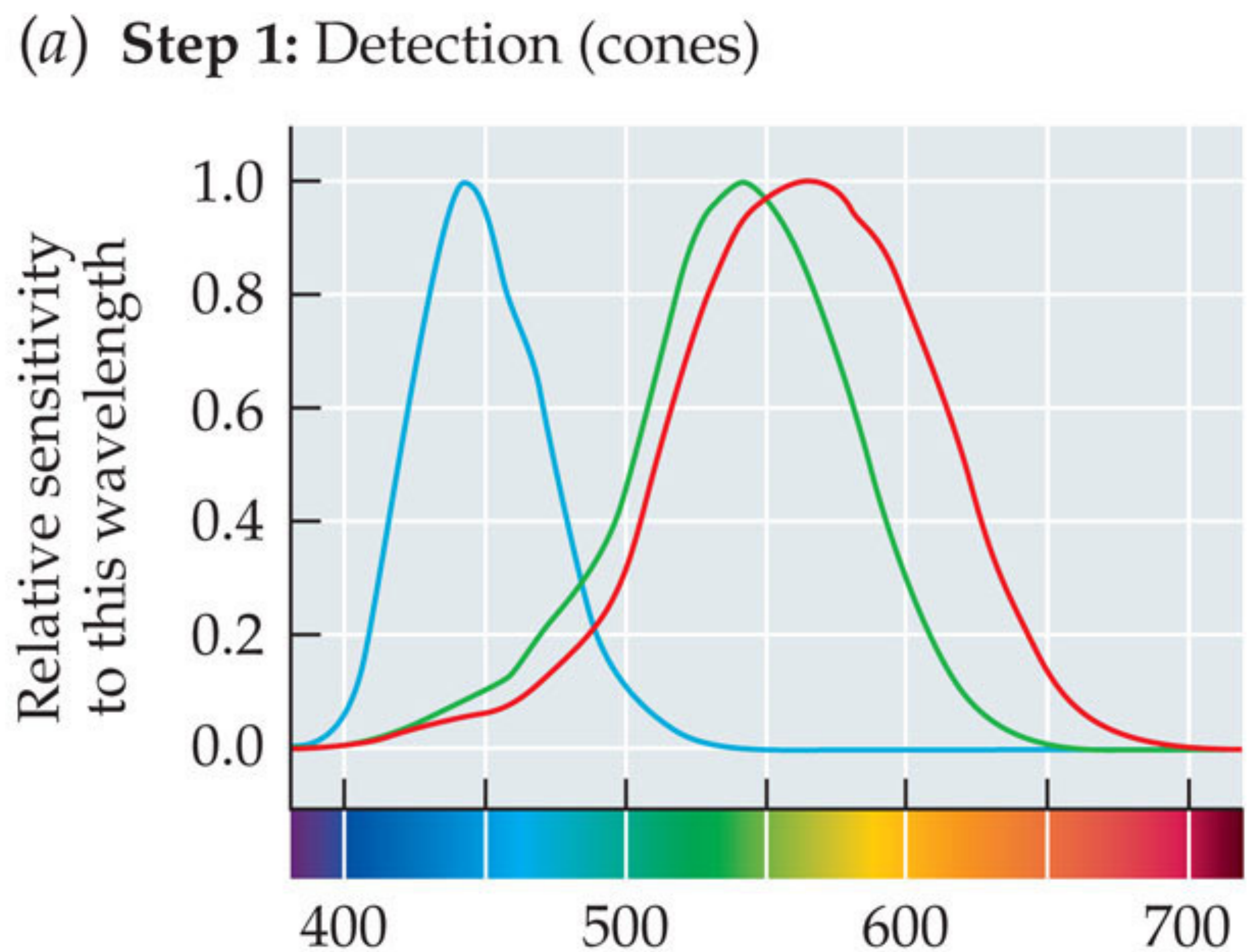


Fig. 9. Color space in terms of our provisional axes (P_1 and P_2) and CIE chromaticity diagram showing unique red-green axis (R-G, coincident within experimental error with cardial axis, P_1), trianopic axis (T), and unique yellow-blue axis (Y-B) for observer J.K.

Krauskopf, J., Williams, D. R., and Heeley, D. W. (1982). Cardinal directions of color space. *Vision Research*, 22:1123–1131.

Summary: cone-opponent and colour-opponent mechanisms

Step 1: Detection—S, M, and L cones detect light.



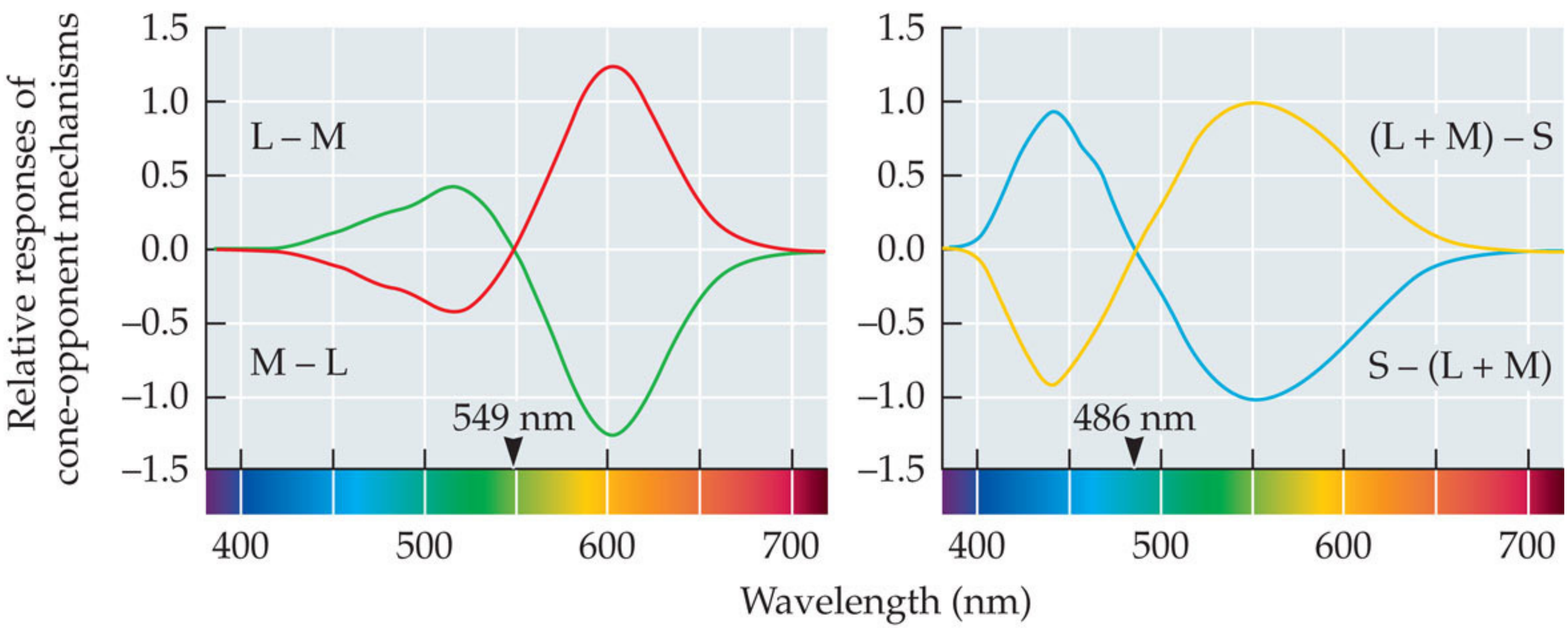
Summary: cone-opponent vs colour-opponent mechanisms

Step 2: Discrimination—cone-opponent mechanisms discriminate wavelengths.

[L – M] and [M – L] compute "red vs. green|".

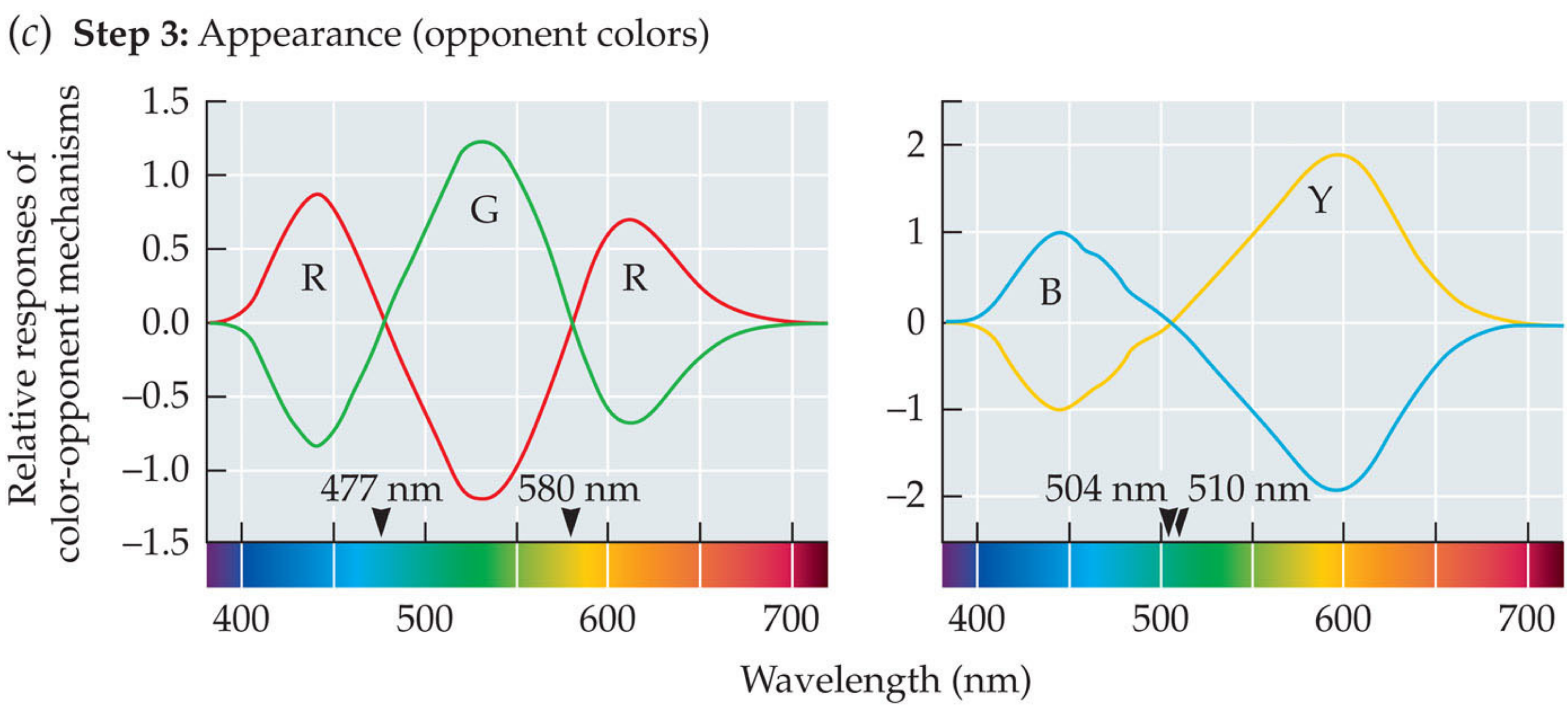
[L + M] – S and S – [L + M] compute "blue vs. yellow".

(*b*) **Step 2:** Discrimination



Summary: cone-opponent vs colour-opponent mechanisms

Step 3: Appearance—further recombination of the signals creates final color-opponent appearance.



***SENSATION & PERCEPTION 4e*, Figure 5.17 (Part 2)**

Individual differences in colour perception

Individual Differences in Color Perception

Qualia: Private conscious experiences of sensation and perception.

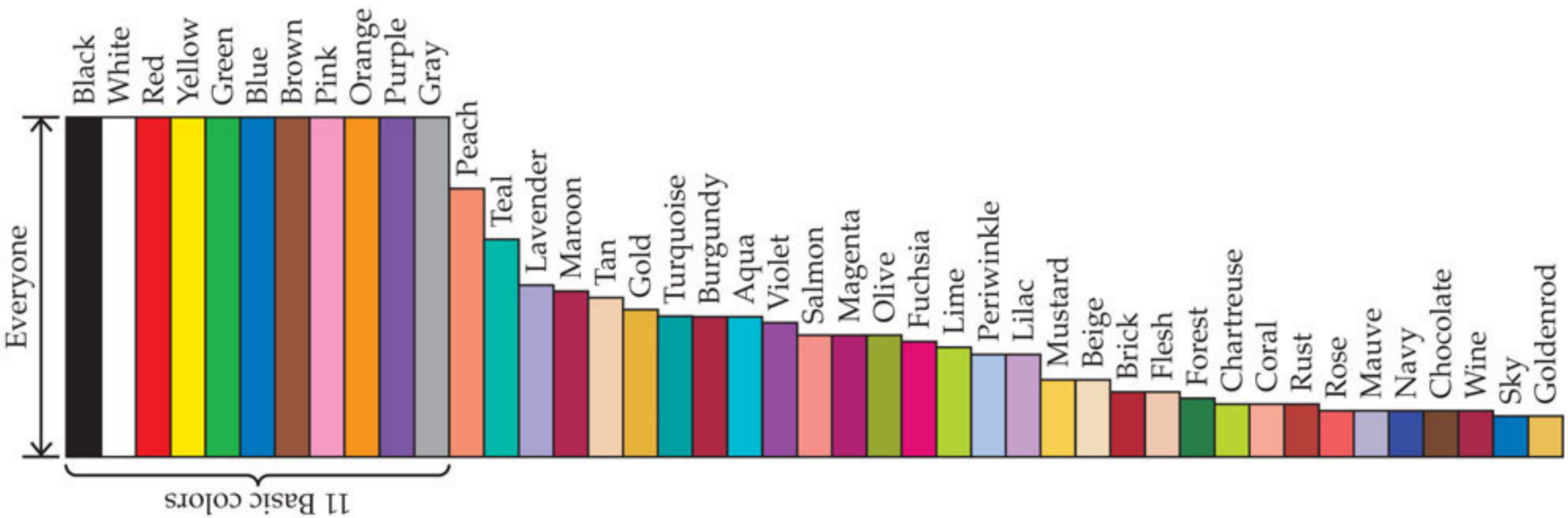
- The question, "Is my perception of blue the same as your perception of blue?" is a question about qualia.

An interesting question, then, is "Does everyone see colors the same way?"

Does everyone see colors the same way?—Yes.

- General agreement on colors, very large agreement on color matching!
- Basic color terms: Single words that describe colors and have meanings that are agreed upon by speakers of a language.

When Lindsey and Brown (2006) asked Americans to name color patches, everyone used the 11 "basic" colors



SENSATION & PERCEPTION 4e, **Figure 5.19**

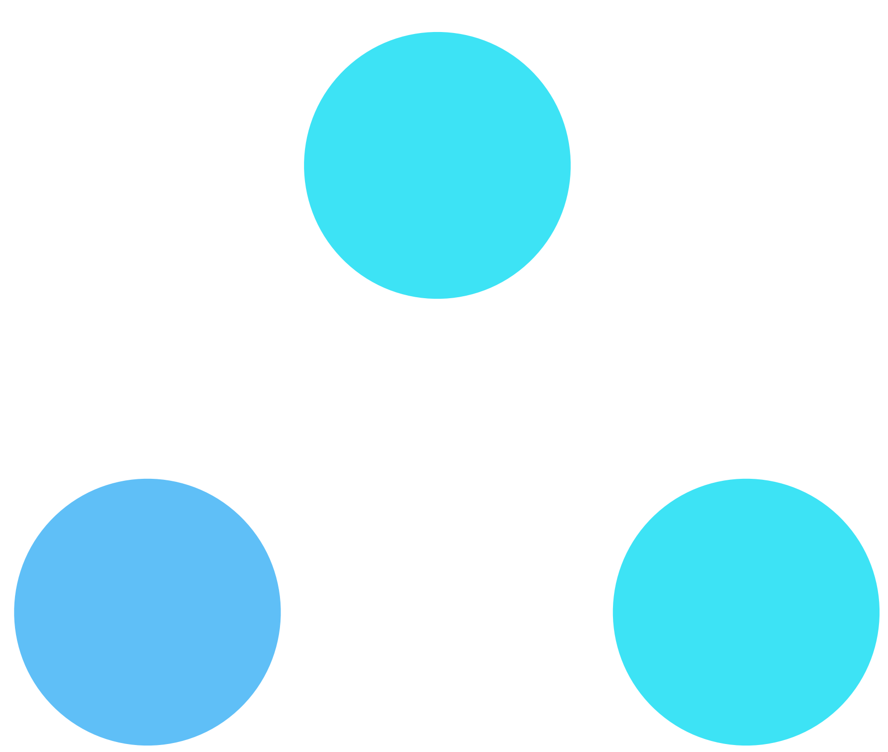
Individual Differences in Colour Perception

Does everyone see colours the same way?—Maybe.

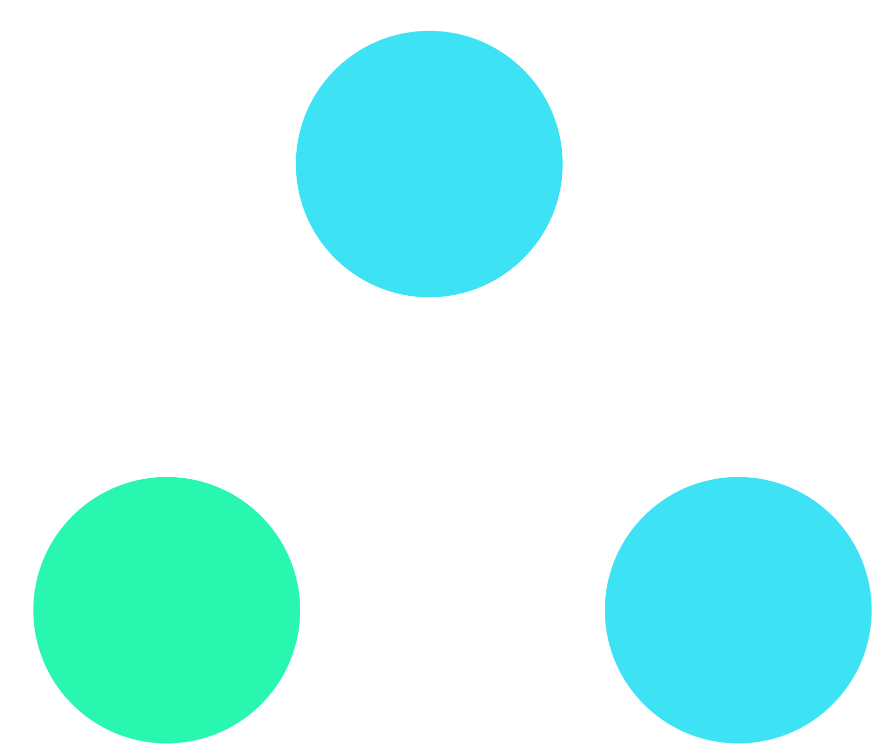
Various cultures describe colour differently (separation of colour from surface texture and material; shiny qualities, metallic).

Cultural relativism: In sensation and perception, the idea that basic perceptual experiences (e.g., color perception) may be determined in part by the cultural environment.

Colour memory experiments:



Harder choice



Easier choice

Individual Differences in Color Perception

Does everyone see colors the same way?—No.

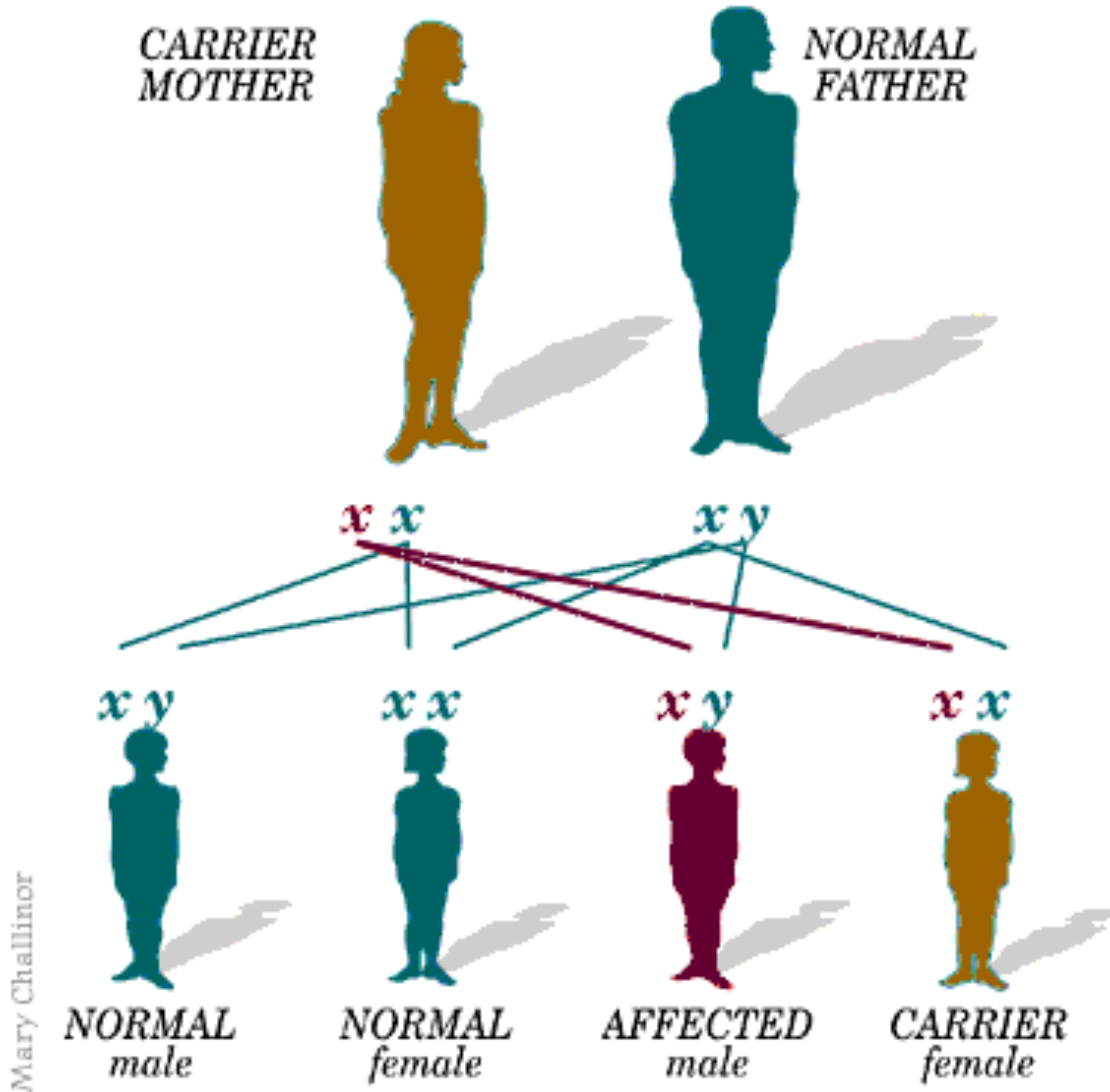
- About 8% of male population and 0.5% of female population has some form of color vision deficiency: "color blindness."
- Color-anomalous: A term for what is usually called "color blindness." Most "color-blind" individuals can still make discriminations based on wavelength. Those discriminations are just different from the norm.

Individual Differences in Color Perception

Several types of color-blind/color-anamolous people

- Deuteranope: Due to absence of M-cones.
- Protanope: Due to absence of L-cones.
- Tritanope: Due to absence of S-cones.
- Cone monochromat: Has only one cone type; truly color-blind.
- Rod monochromat: Has no cones of any type; truly color-blind and very visually impaired in bright light.
- Achromatopsia: Inability to see color due to cortical damage.
- Anomia: Inability to name objects or colors in spite of the ability to see and recognize them. Typically due to brain damage.

Genetics of Colour Anomalies

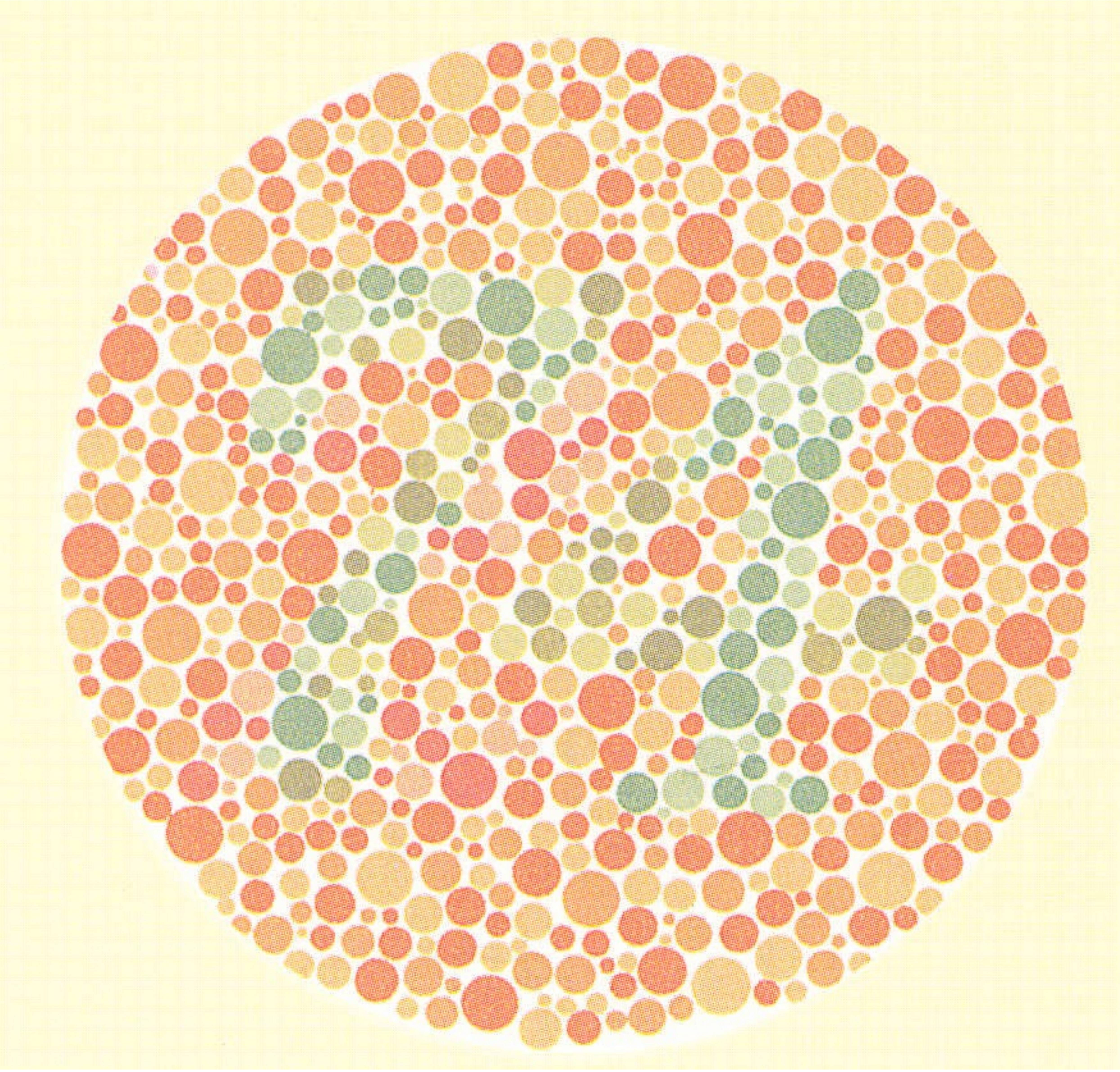


Incidence of Colour Anomalies

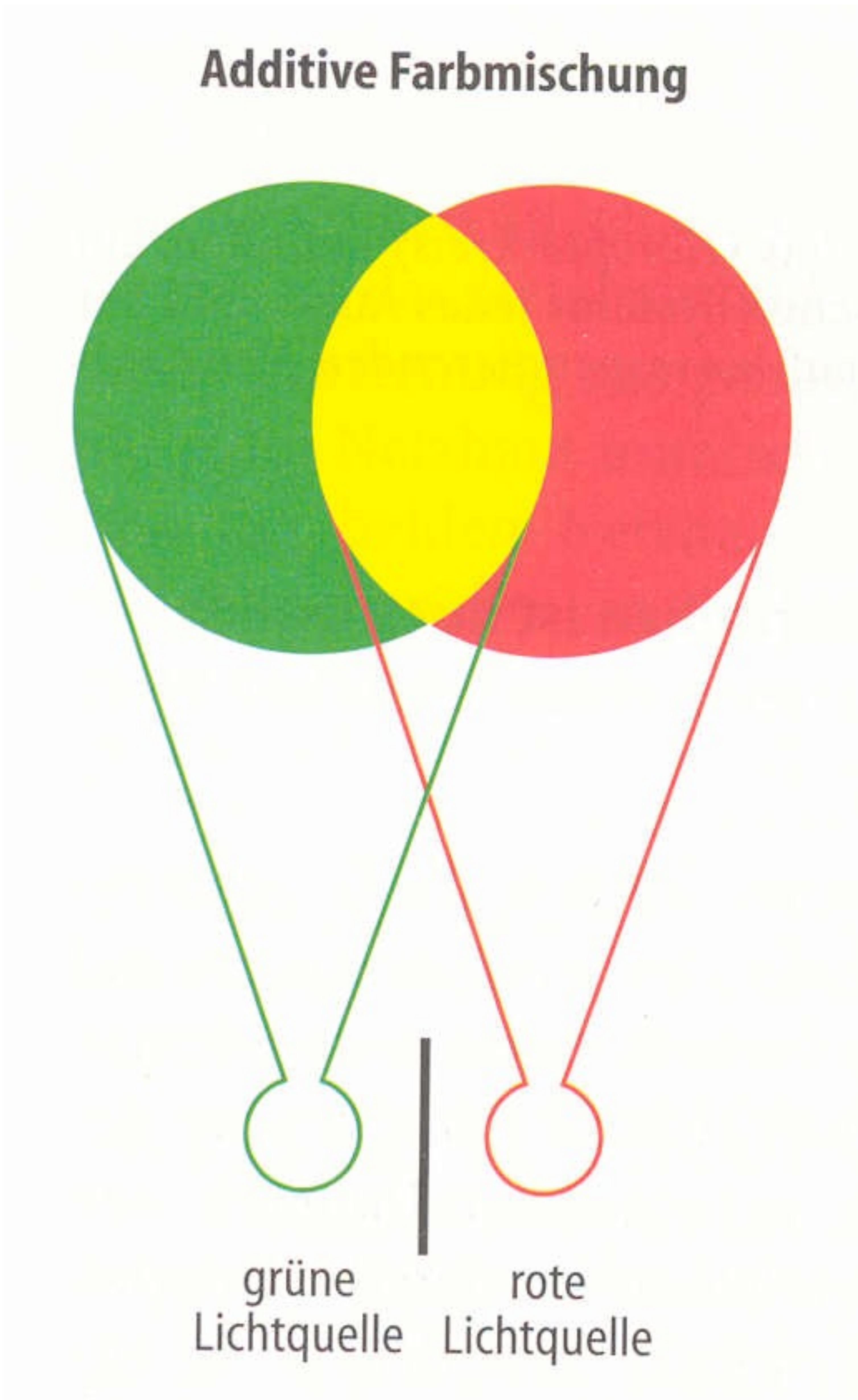
	male	female
Protanopen (L-Zapfen fehlen)	1.0	0.02
Deuteranopen (M-Zapfen fehlen)	1.1	0.01
Tritanopen (S-Zapfen fehlen)	0.002	0.001
Protanomal	1.0	0.02
Deuteranomal	4.9	0.38
Tritanomal	0.002	0.001
Stäbchen-Monochromaten	0.003	0.002

(all numbers in %)

Testing for colour blindness: Ishihara colour plates



Testing for colour blindness: Anomaloscope



Foveal additive color mixing of a 2 degree field

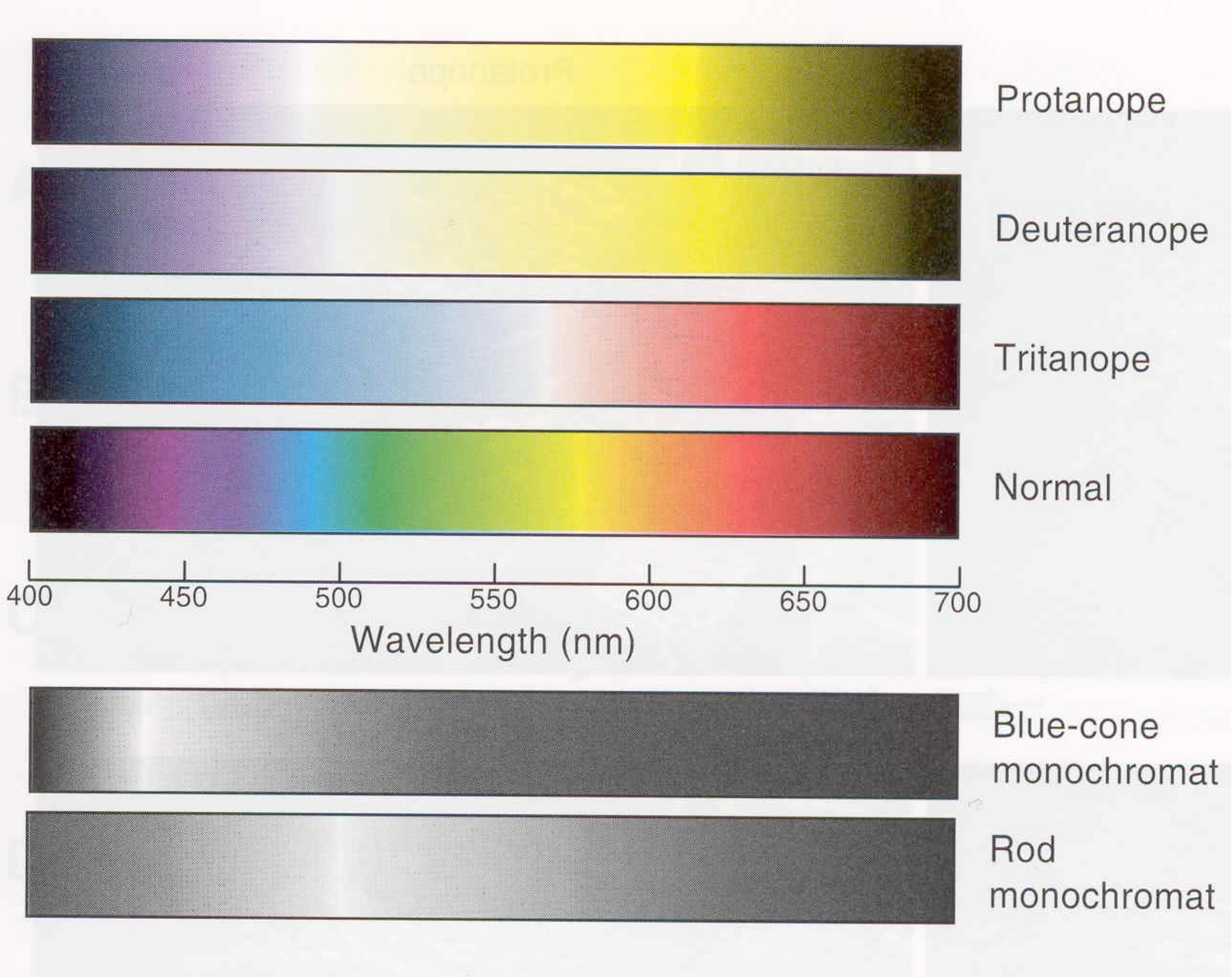
red (671 nm) + green (546 nm) ~ yellow (589 nm)

Normal: Green/Red ~ 1 (AQ = 0.7-1.4)

Protanomaly (more red): AQ = 0.6-0.11

Deutanomaly (more green): AQ = 2.0-20

Simulation of Colour Anomalies



Simulation of Colour Anomalies

From the colour of lights to a world of colour

From the Color of Lights to a World of Color

Colors very rarely appear in isolation. Usually, many colors are present in a scene.

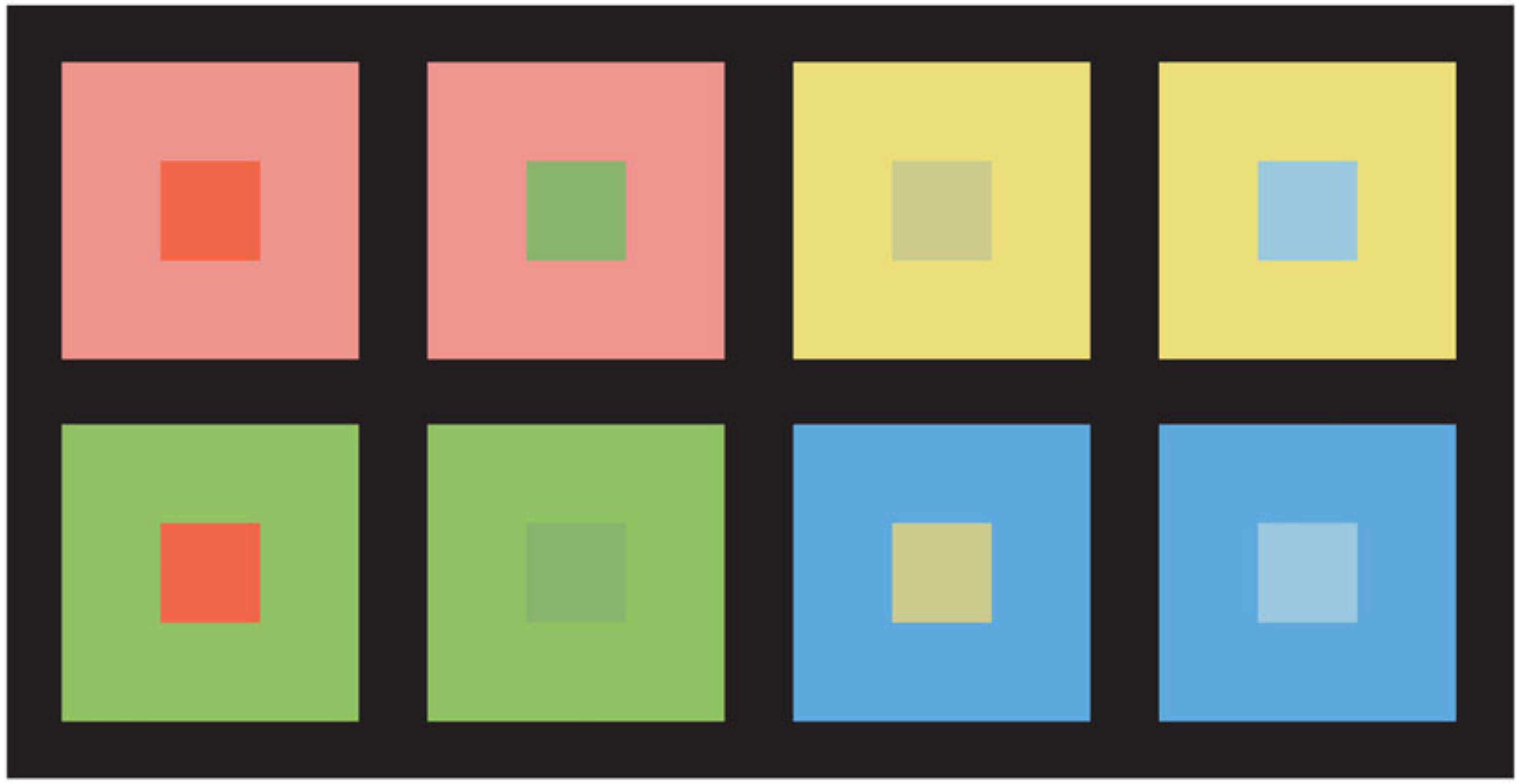
When many colors are present, they can influence each other.

Color contrast and color assimilation

Color contrast: A color perception effect in which the color of one region induces the opponent color in a neighboring region.

Color assimilation: A color perception effect in which two colors bleed into each other, each taking on some of the chromatic quality of the other.

(*a*) Color contrast



From the Color of Lights to a World of Color

Unrelated color: A color that can be experienced in isolation.

Related color: A color, such as brown or gray, which is seen only in relation to other colors: A "gray" patch in complete darkness appears white.

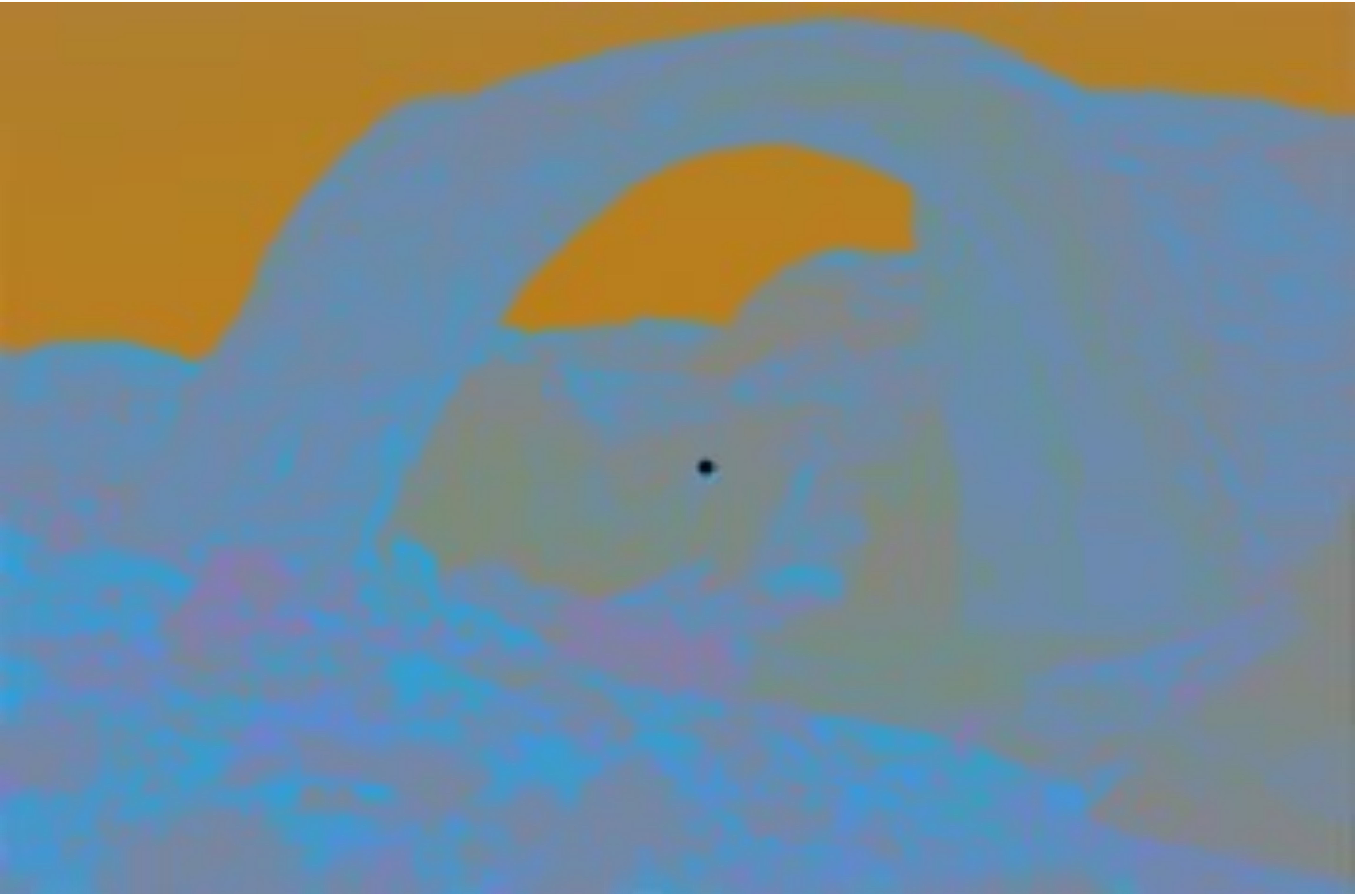
Afterimages: A visual image seen after a stimulus has been removed.

Negative afterimage: An afterimage whose polarity is the opposite of the original stimulus.

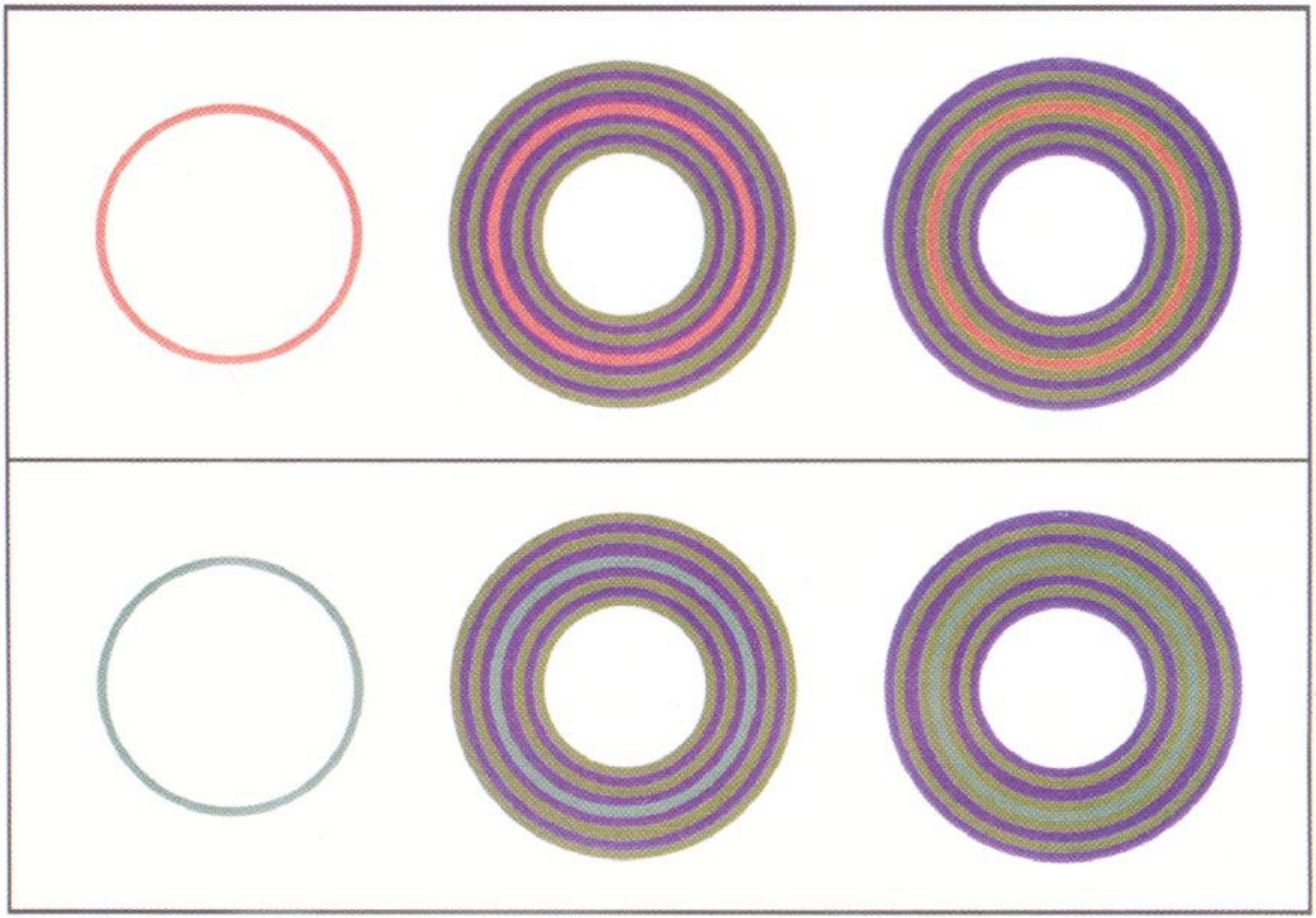
Light stimuli produce dark negative afterimages.

Colors are complementary. Red produces green afterimages and blue produces yellow afterimages (and vice versa).

This is a way to see opponent colors in action.



There is more to Colour: Context, Colour Constancy …



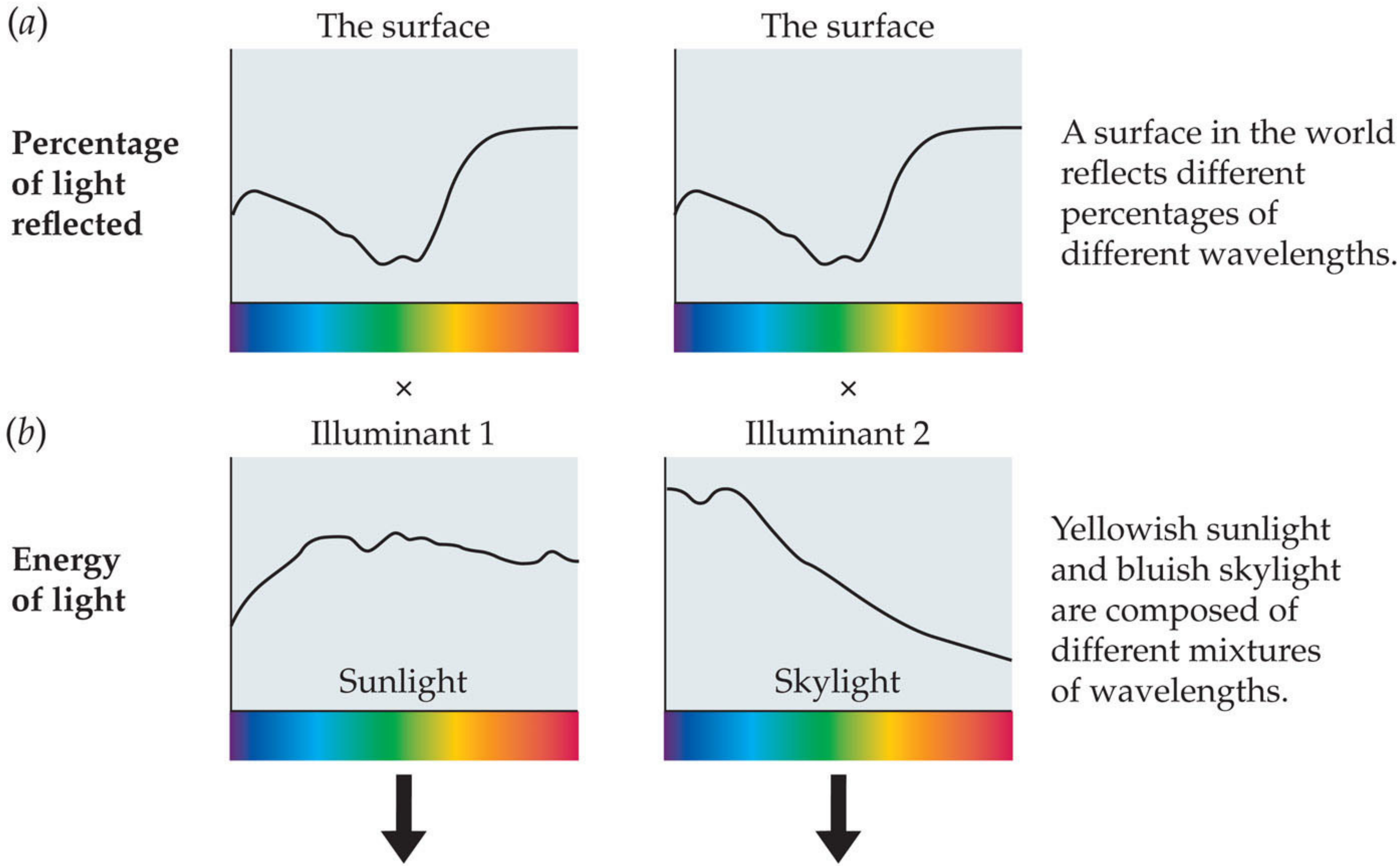
From the Color of Lights to a World of Color

Color constancy: The tendency of a surface to appear the same color under a fairly wide range of illuminants.

To achieve color constancy, we must discount the illuminant and determine what the true color of a surface is regardless of how it appears.

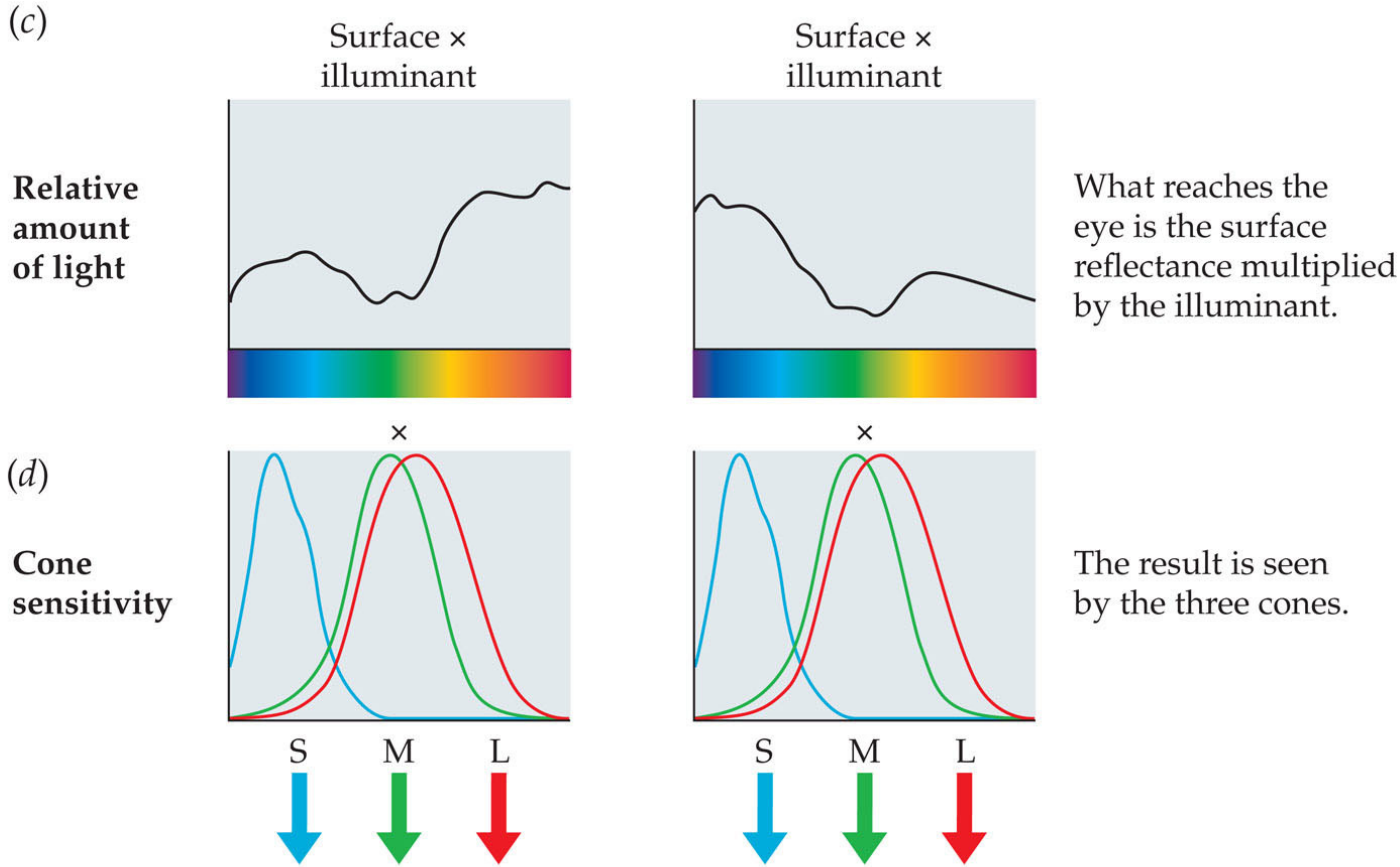
Illuminant: The light that illuminates a surface.

Color constancy (1/3)



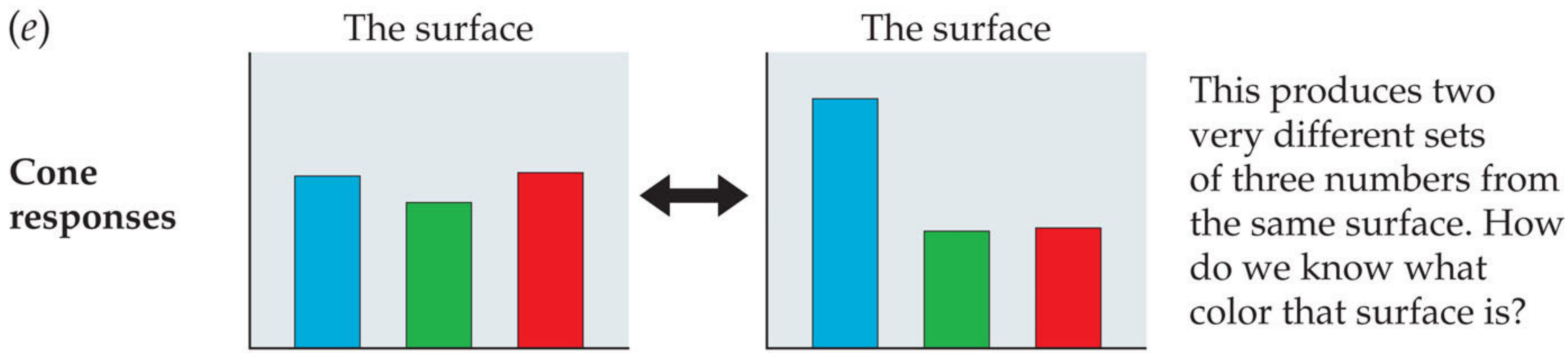
***SENSATION & PERCEPTION 4e*, Figure 5.23 (Part 1)**

Color constancy (2/3)



SENSATION & PERCEPTION 4e, Figure 5.23 (Part 2)

Color constancy (3/3)



SENSATION & PERCEPTION 4e, **Figure 5.23 (Part 3)**

From the Color of Lights to a World of Color

Only taking (physical) constraints into the calculation make constancy possible.

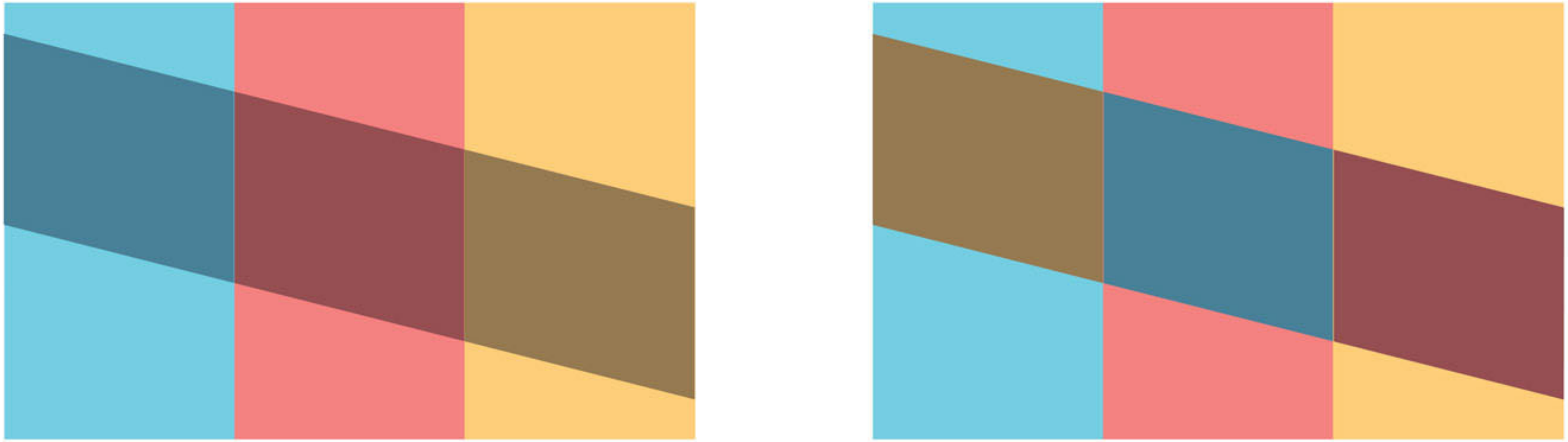
- Intelligent guesses about the illuminant
- Assumptions about light sources
- Assumptions about surfaces

In our visual system many mechanisms appear to be involved, e.g. normalisations across receptor outputs, normalisations across patches of the scene, or even the entire visual field, memory colours … . (At least one lecture in its own right!)

The visual system “knows” that brightness changes across a shadow boundary, but hue does not

(*a*) Luminance change without hue change looks like a shadow.

(*b*) Luminance change *with* hue change looks less like a shadow.



***SENSATION & PERCEPTION* 4e, Figure 5.24**

Akiyoshi Kitaoka
@AkiyoshiKitaoka

2色法によるイチゴの錯視。この画像はすべてシアン色（青緑色）の画素でできているが、イチゴは赤く見える。

Strawberries appear to be reddish, though the pixels are not.

2:07 AM - Feb 28, 2017

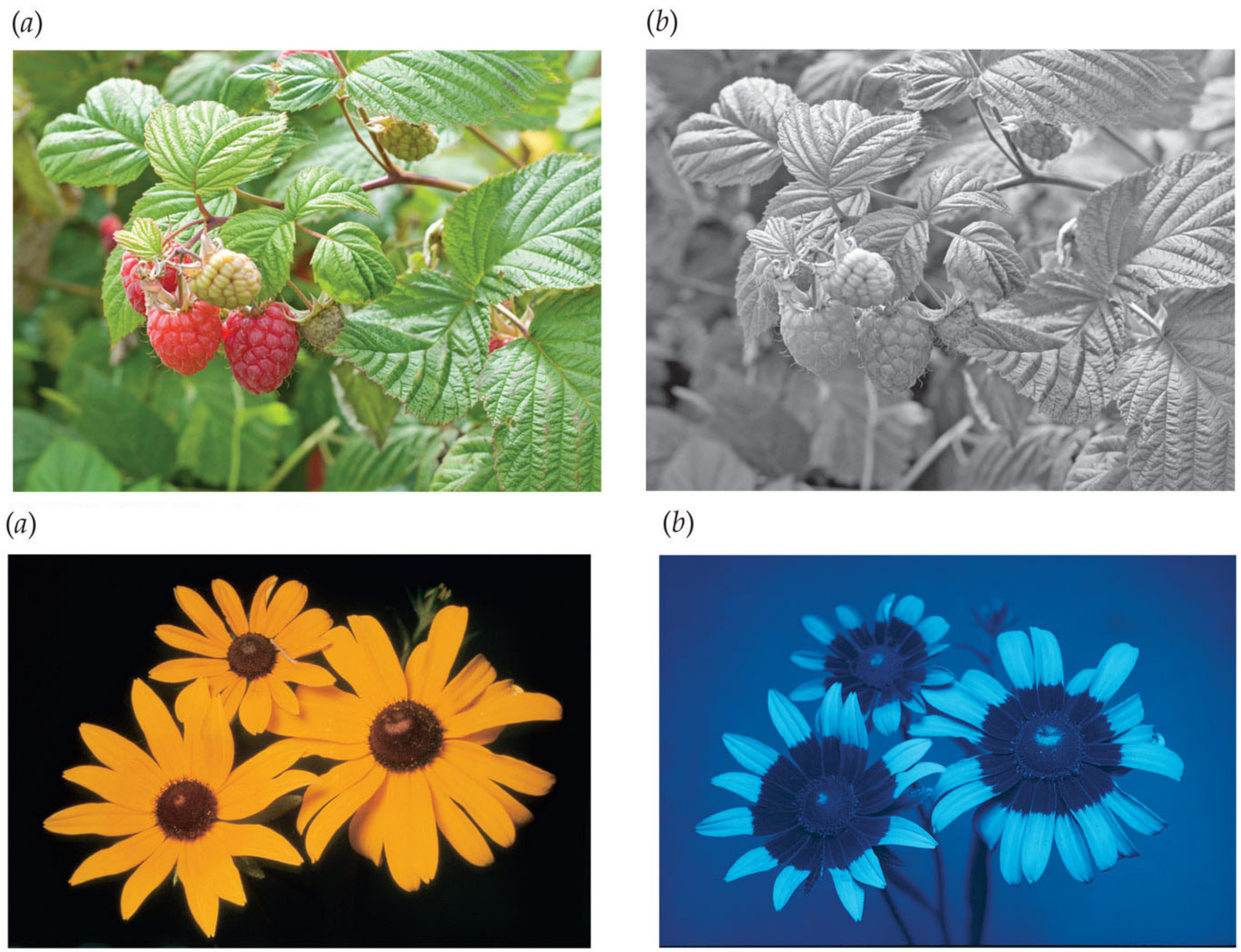
121 4,725 9,490

What is colour vision good for?

What is Colour Vision Good For?

Animals provide insight into colour perception in humans

Food: It is easier to find berries and determine when they are ripe with colour vision. Some flowers have ultraviolet markings that only bees can see.

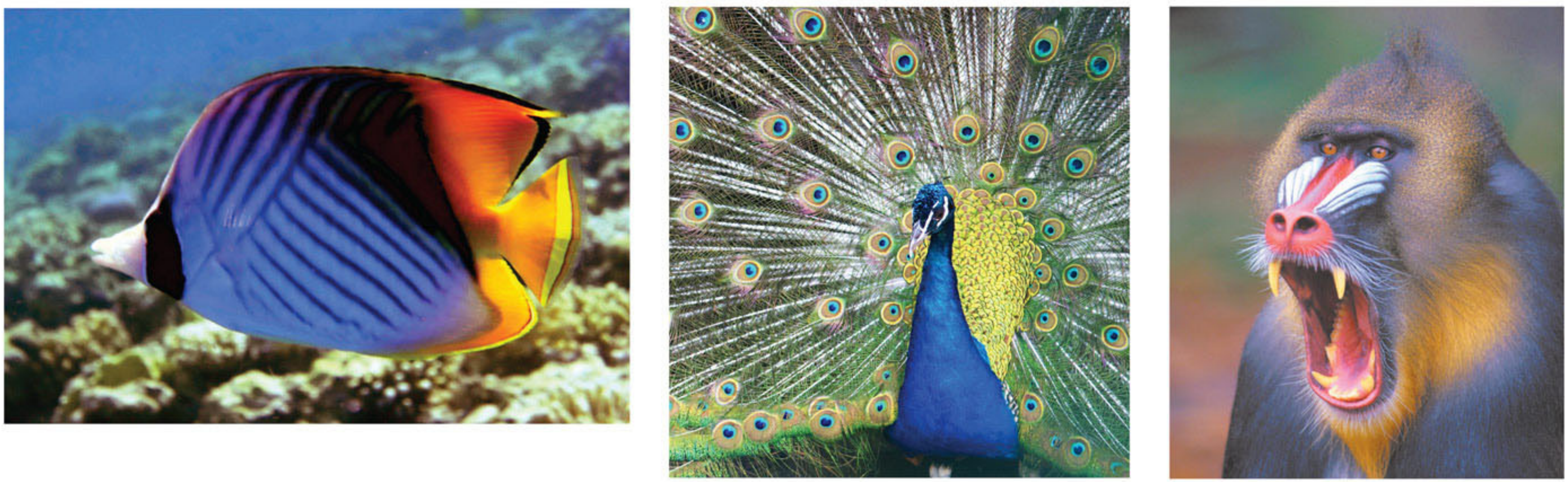


SENSATION & PERCEPTION 4e, Figure 5.28

What is Color Vision Good For?

Sex: Flower colors are advertisements for bees to trade food for sex (for pollination). Colorful patterns on tropical fish and toucans provide sexual signals.

(a) (b) (c)



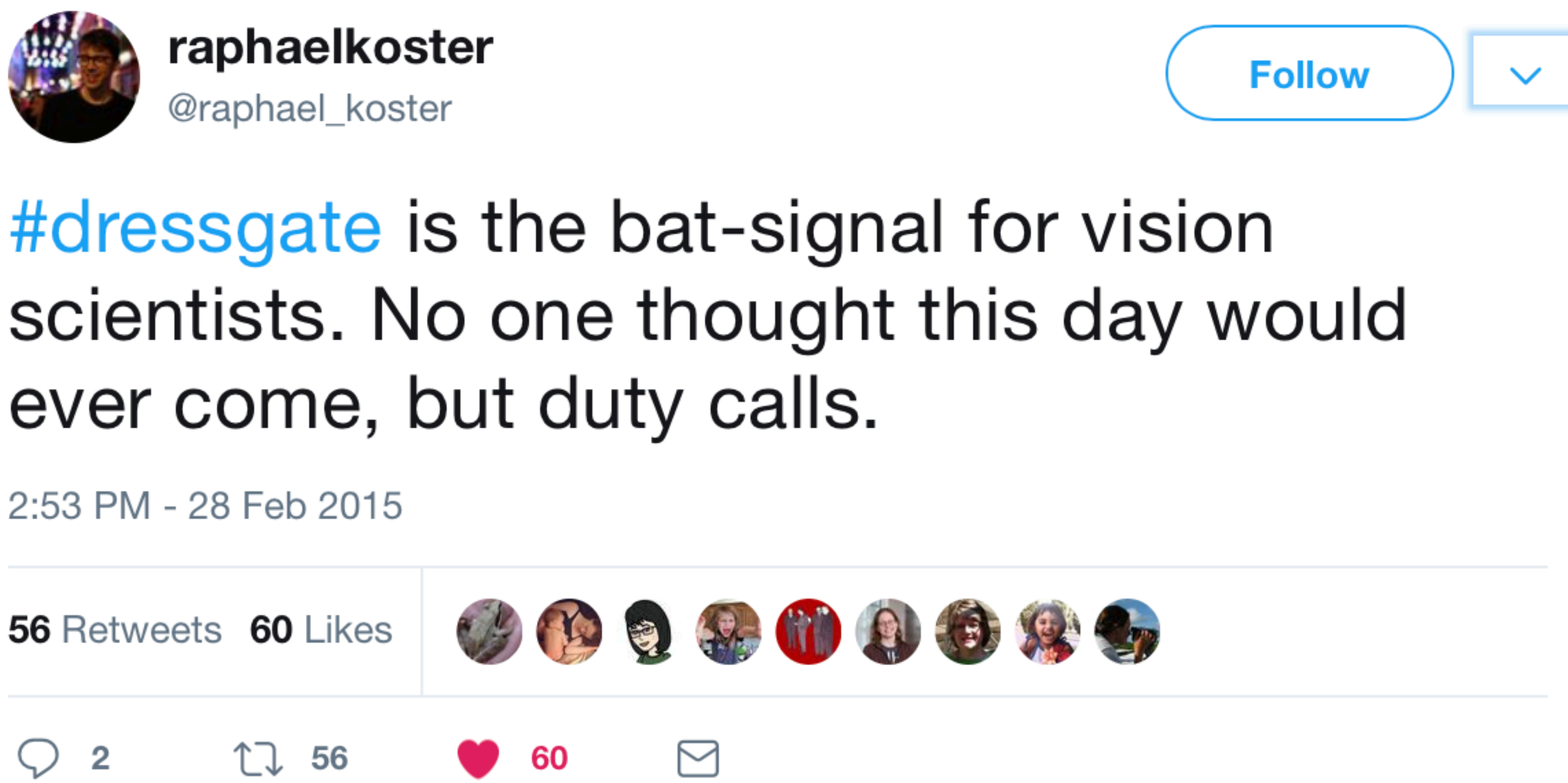
SENSATION & PERCEPTION 4e, **Figure 5.29**

Individual differences in colour perception: redux

Individual Differences in Color Perception

Does everyone see colors the same way?—No.

Individual Differences in Color Perception



Individual Differences in Color Perception

The very existence of "the dress" challenged our entire understanding of color vision. Up until early 2015, a close reading of the literature could suggest that the entire field had gone somewhat stale—we thought we basically knew how color vision worked, more or less. The dress upended that idea. No one had any idea why some people see "the dress" differently than others—we arguably still don't fully understand it. It was like discovering a new continent. Plus, the stimulus first arose in the wild (in England, no less), making it all the more impressive.

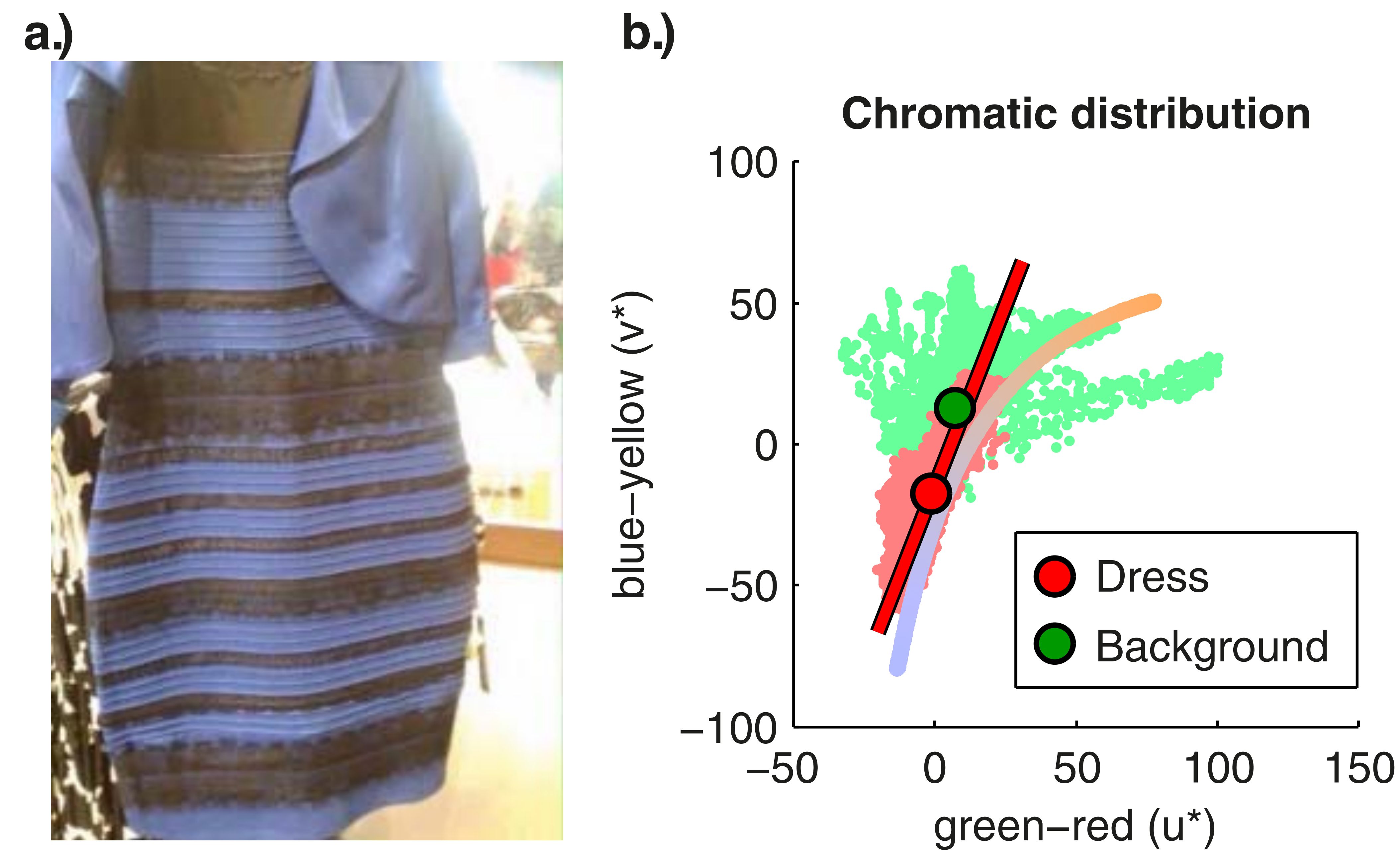
- Pascal Wallisch, writing in *Slate*

http://www.slate.com/articles/health_and_science/science/2017/04/here_s_why_people_saw_the_dress_differently.html

Individual Differences in Color Perception

The colours present in the dress seem to fall neatly along the Planckian locus (daylight axis).

Average variation in the background aligns with the average variation in the dress.



Witzel et al., 2017

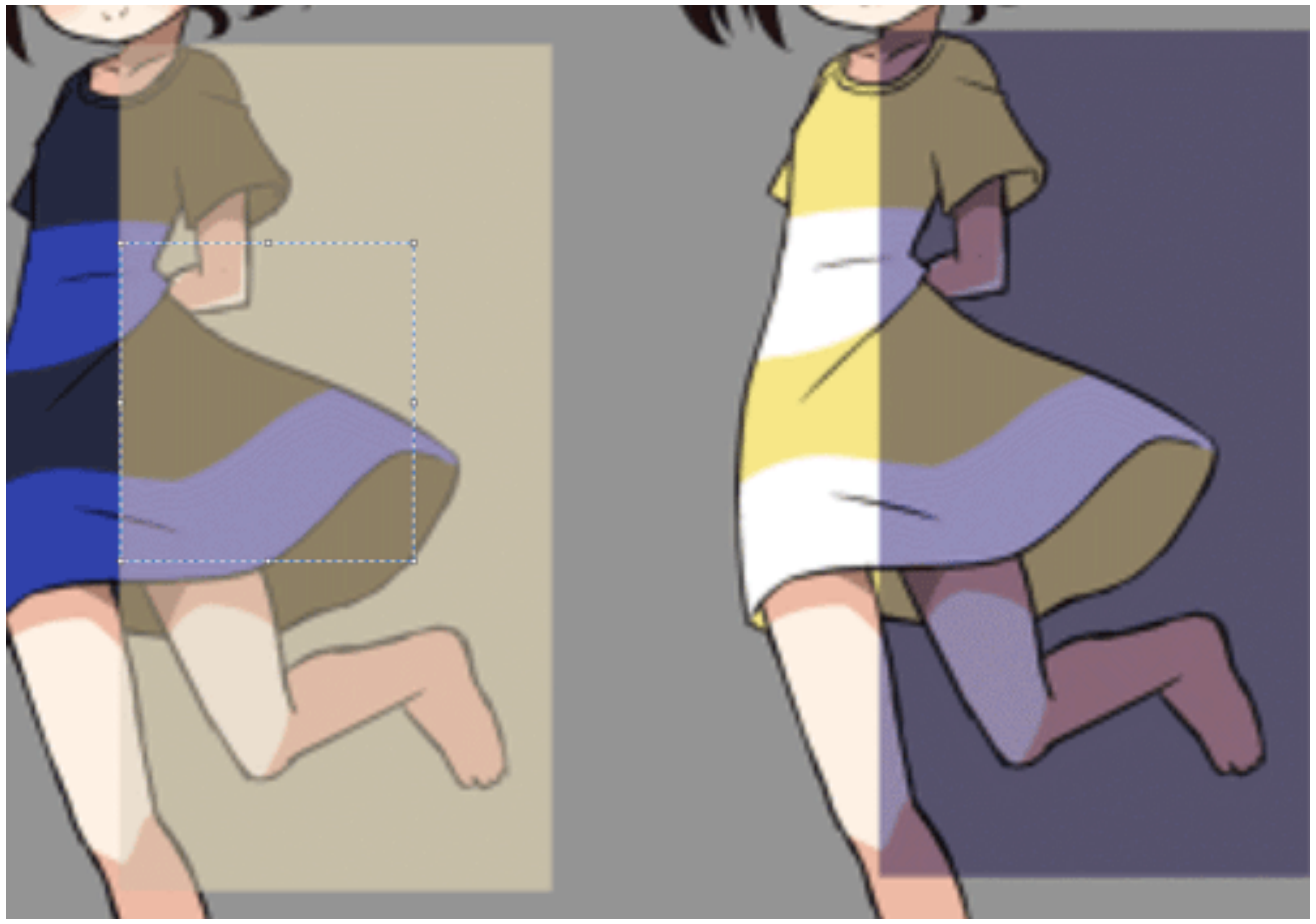
http://www.slate.com/articles/health_and_science/science/2017/04/here_s_why_people_saw_the_dress_differently.html

Individual Differences in Color Perception

Perception of the dress seems to be tied to an individual's interpretation of the illuminant.

If you assume the dress is in shadow or in natural light, you're much more likely to see it as white and gold. Why?

- Shadows overrepresent blue light. Mentally-subtracting short-wavelength light will make an image look yellow-ish.
- Similarly, natural daylight also over-represents short-wavelengths (blue sky)



http://www.slate.com/articles/health_and_science/science/2017/04/here_s_why_people_saw_the_dress_differently.html

Individual differences in colour perception

Wallisch (2017) studied this in a large (13000 participants) online survey.

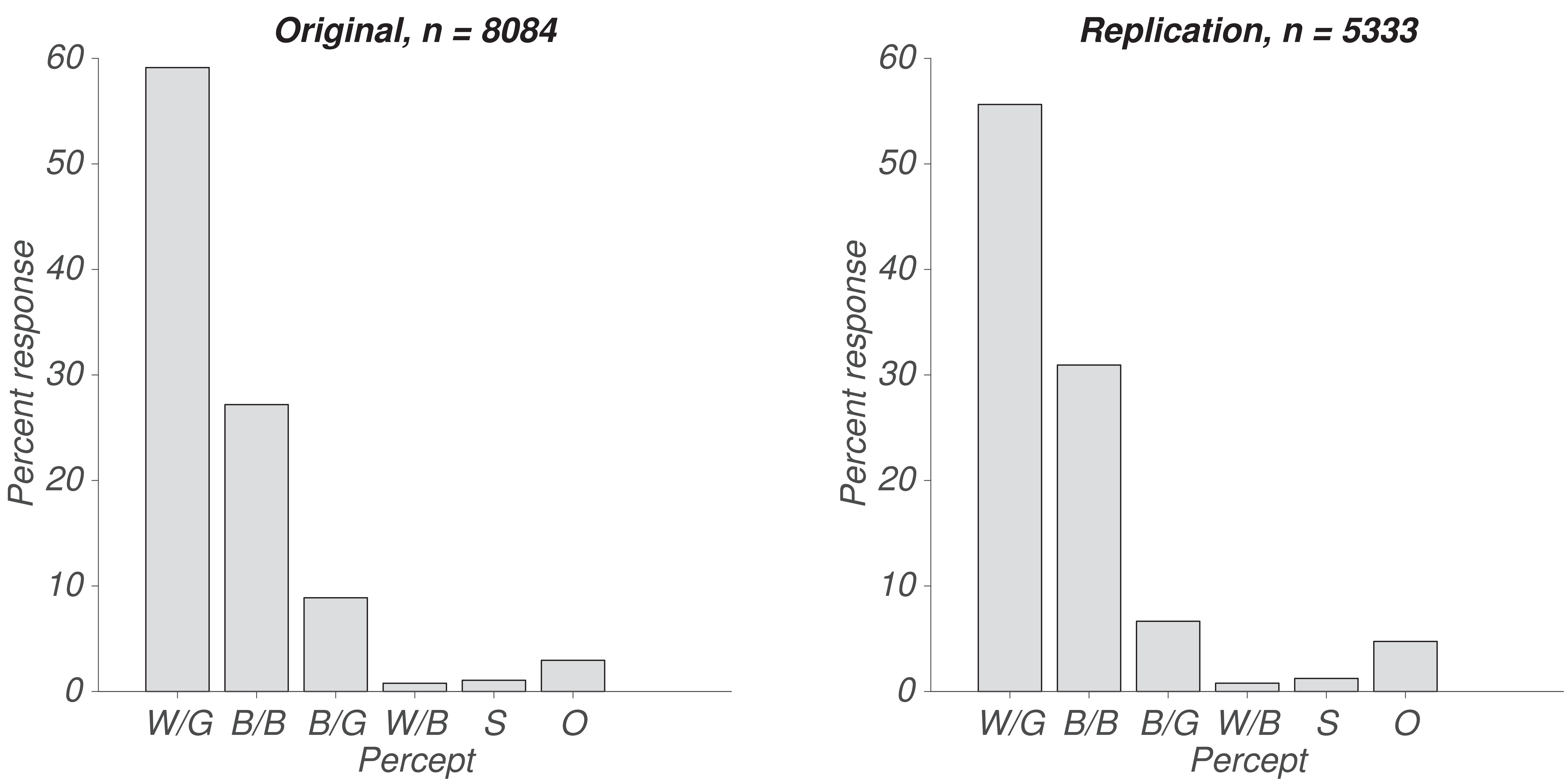
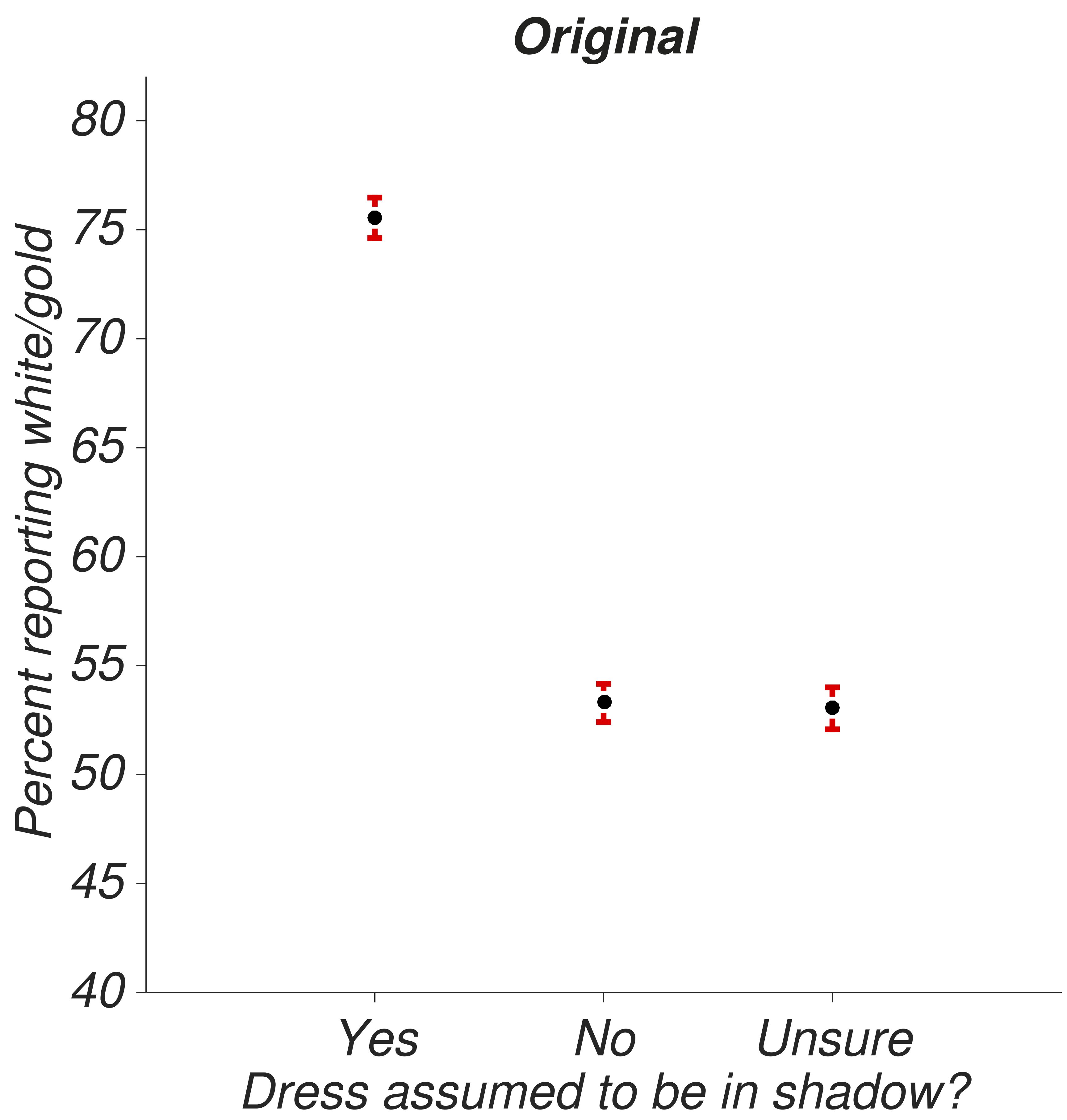
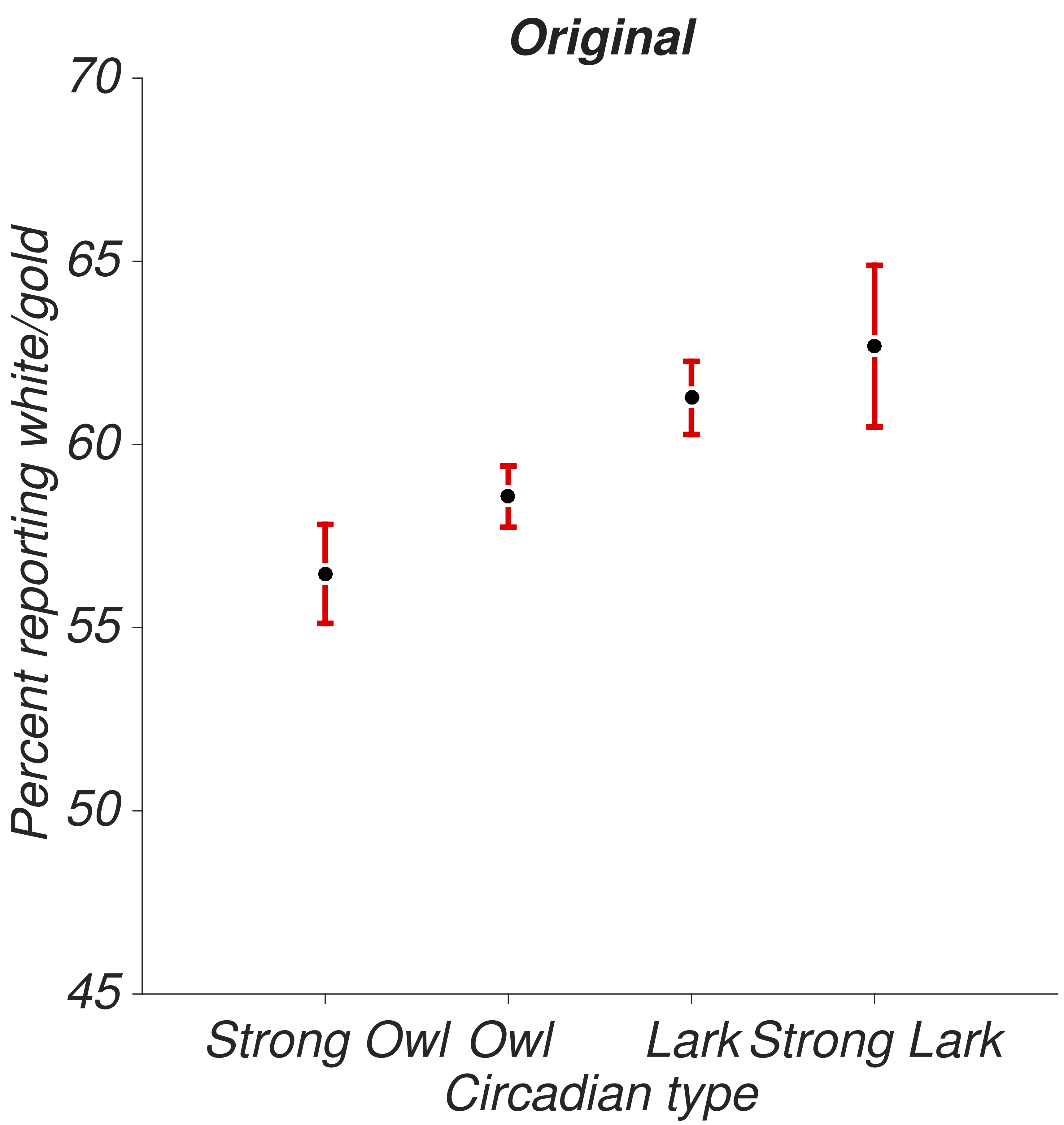


Figure 1. Color percept of participants upon first seeing the dress stimulus. The *x*-axis represents the categorical response. W/G = white and gold, B/B = blue and black, B/G = blue and gold, B/W = black and white, S = switching or bistable, O = other. The *y*-axis represents the proportion of participants that report seeing the dress stimulus in this way, in percentages. Left panel: data from Run 1; right panel: data from Run 2.

Individual differences in colour perception





Colour Vision Summary

First stage of colour vision well described by the Young-Helmholtz trichromatic theory of colour vision: Three primary colours corresponding to cone sensitivities. Explains colour matching experiments, metamers and colour anomalies.

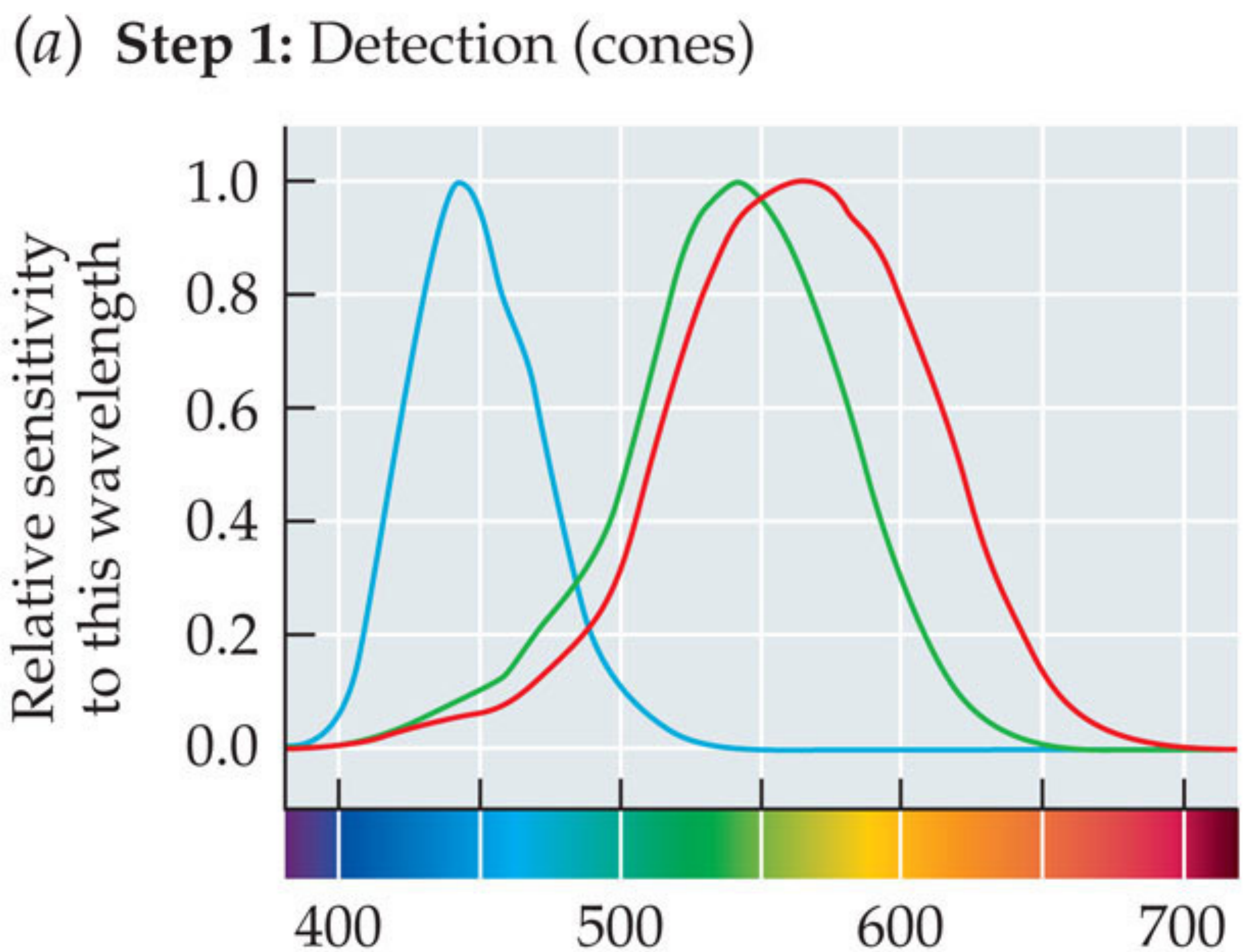
The second stage is the cardinal axes of colour space (DKL), corresponding to cone opponency, and consistent with things like aftereffects, colour adaptation and masking.

Third stage of"colour appearance", which is similar to but not exactly the cardinal axes, and corresponds to Hering's opponent colours and the unique hues derived from hue cancellation experiments.

There are, however, additional contextual or "higher-order" effects not explicable with either of the two (lower-level) colour theories.

Summary: cone absorption

Step 1: Detection—S, M, and L cones detect light.



Evidence:

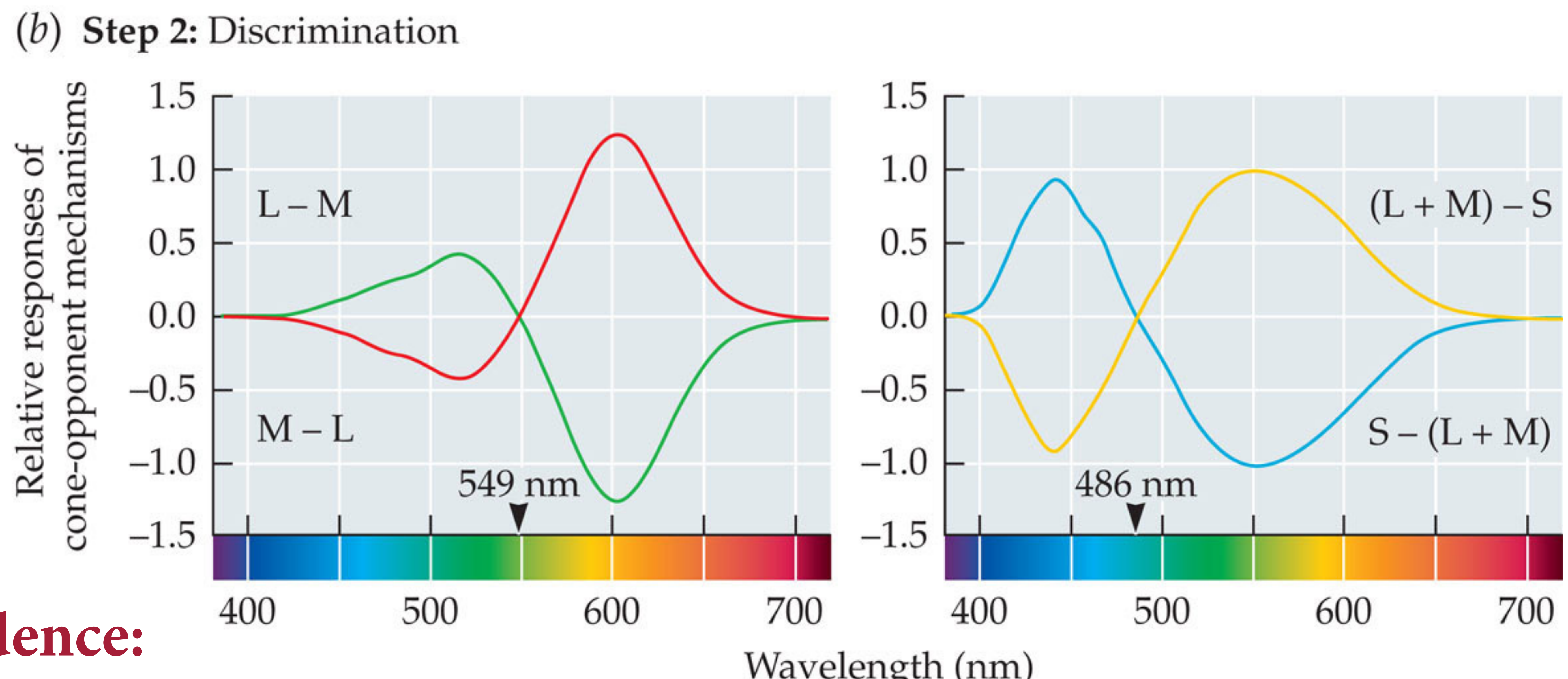
- **Trichromatic colour matching**
- **Metamers and Grassman's laws**

Summary: cone-opponent mechanism

Step 2: Discrimination—cone-opponent mechanisms discriminate wavelengths.

[L – M] and [M – L] compute "red vs. green|".

[L + M] – S and S – [L + M] compute "blue vs. yellow".

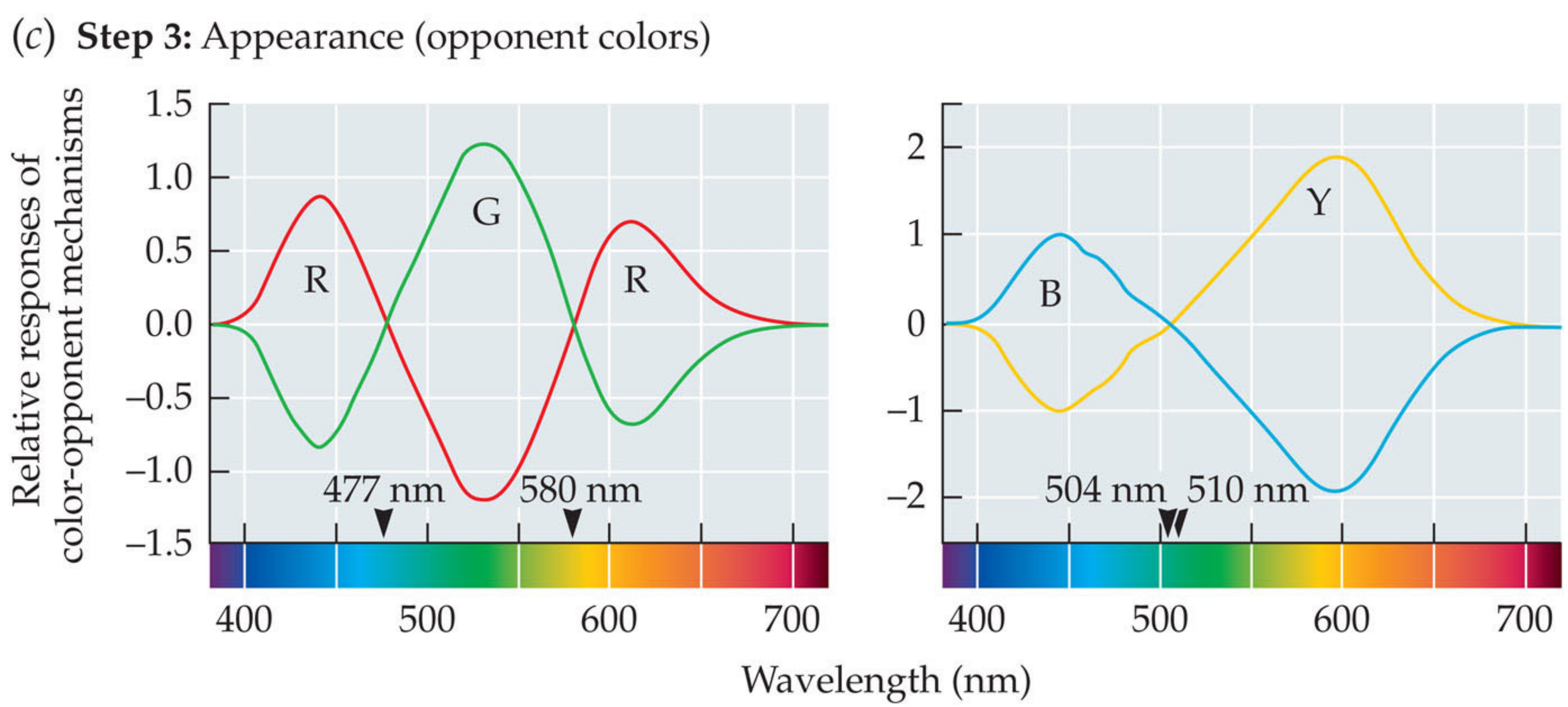


Evidence:

- **Efficient coding suggests cone responses should be de-correlated**
- **Selective adaptation along cardinal colour axes (cone-opponent axes)**
- **Masking effects consistent with three cone-opponent mechanisms (L-M, S-(L+M), L+M noise and signals)**

Summary: colour-opponent mechanisms

Step 3: Appearance—further recombination of the signals creates final color-opponent appearance.



SENSATION & PERCEPTION 4e, Figure 5.17 (Part 2)

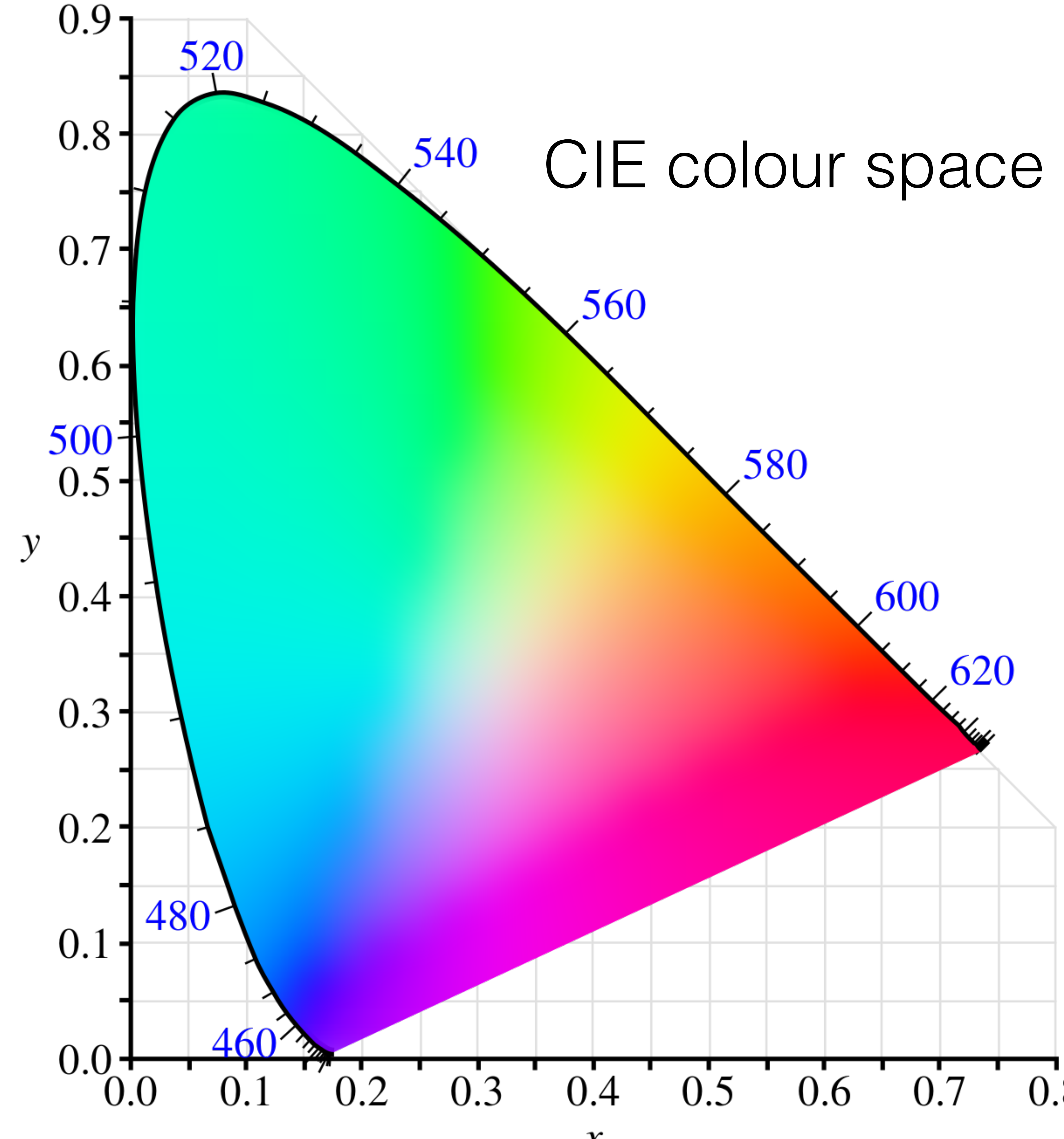
Evidence:
- **(Subjective) appearance and the hue cancellation experiment**
- **Unique hues: R-G cardinal axis like R-G unique axis, but B-Y cardinal axis (from adaptation) does not align completely with B-Y unique axis (from appearance)**

Unique hues

Magenta, e.g., is not a *unique hue* because unlike unique red, unique green, unique yellow and unique blue it appears to us as containing two colours, it appears to be contain both blue and red—thus not a *unique* sensation of one colour!

Additional info (not exam relevant): Some colours are *non-spectral colours*, i.e. we can perceive them but there is no monochromatic light corresponding to them, i.e. no laser of that colour.

- Grayscale: white, black, gray
- Any colour mixed with white or black, e.g. pink (reddish plus white) or brown (orange plus gray or black)
- Violet-red including magenta, rose and variations of purple and red
- Metallic colours—surface effect (brightness varying with light angle)



The End

Felix Wichmann

Neural Information Processing Group
Eberhard Karls Universität Tübingen