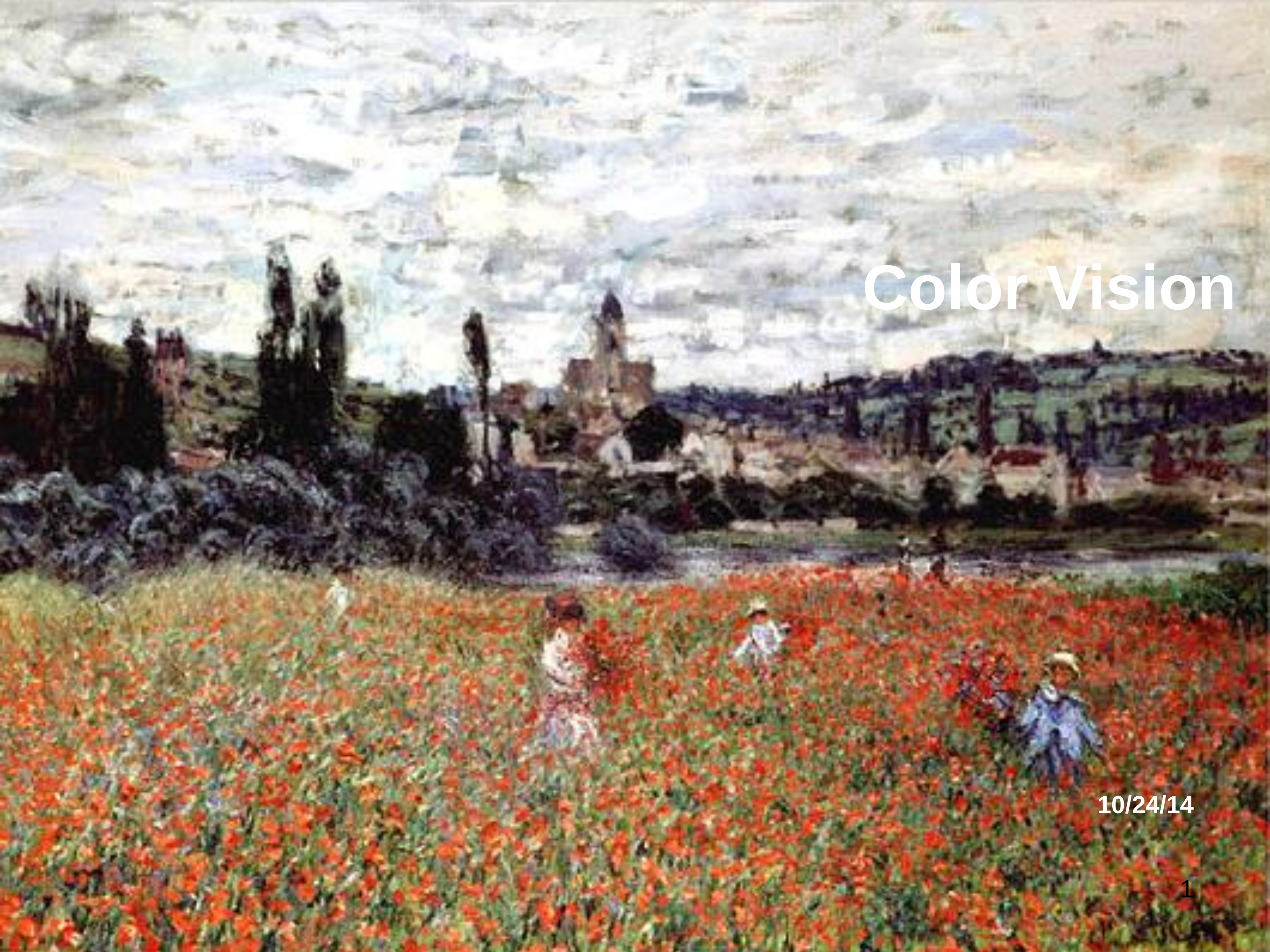


Color Vision

10/24/14

Reminders

- Midterm 1 on Monday.
- Review materials on Ted, in ‘Extra materials’
- Review on Sunday, 3 - 4:50 PM, here.
- Exam includes today’s lecture.

Earlier: How are signals in visual cortex organized?

V1 Cells as feature detectors

- Cells that are **feature detectors**:
  - Simple cortical cell
  - Complex cortical cell
  - End-stopped cortical cell
- These neurons fire to specific features of a stimulus. [Think of these as object edge detectors.]
- Neurons farther along in the visual pathway fire to more complex stimuli in a **hierarchical** manner.
- Good to know for the exam.

TABLE 4.1 Properties of Neurons in the Optic Nerve, LGN, and Cortex

TYPE OF CELL	CHARACTERISTICS OF RECEPTIVE FIELD
Optic nerve fiber (ganglion cell)	Center-surround receptive field. Responds best to small spots, but will also respond to other stimuli.
Lateral geniculate	Center-surround receptive fields very similar to the receptive field of a ganglion cell.
Simple cortical	Excitatory and inhibitory areas arranged side by side. Responds best to bars of a particular orientation.
Complex cortical	Responds best to movement of a correctly oriented bar across the receptive field. Many cells respond best to a particular direction of movement.
End-stopped cortical	Responds to corners, angles, or bars of a particular length moving in a particular direction.

Page 66

Video: Cell responses and perception

We have seen, via single-cell recordings, that individual V1 cortical cells (feature detectors) will respond to specific stimuli. But does our perception match the cellular response?

Do the levels of analysis connect?

We can use the phenomenon of **selective adaptation** to help construct a psychophysics experiment to test the connection between feature detector response and perception.

Video: Cell responses and perception

Selective adaptation

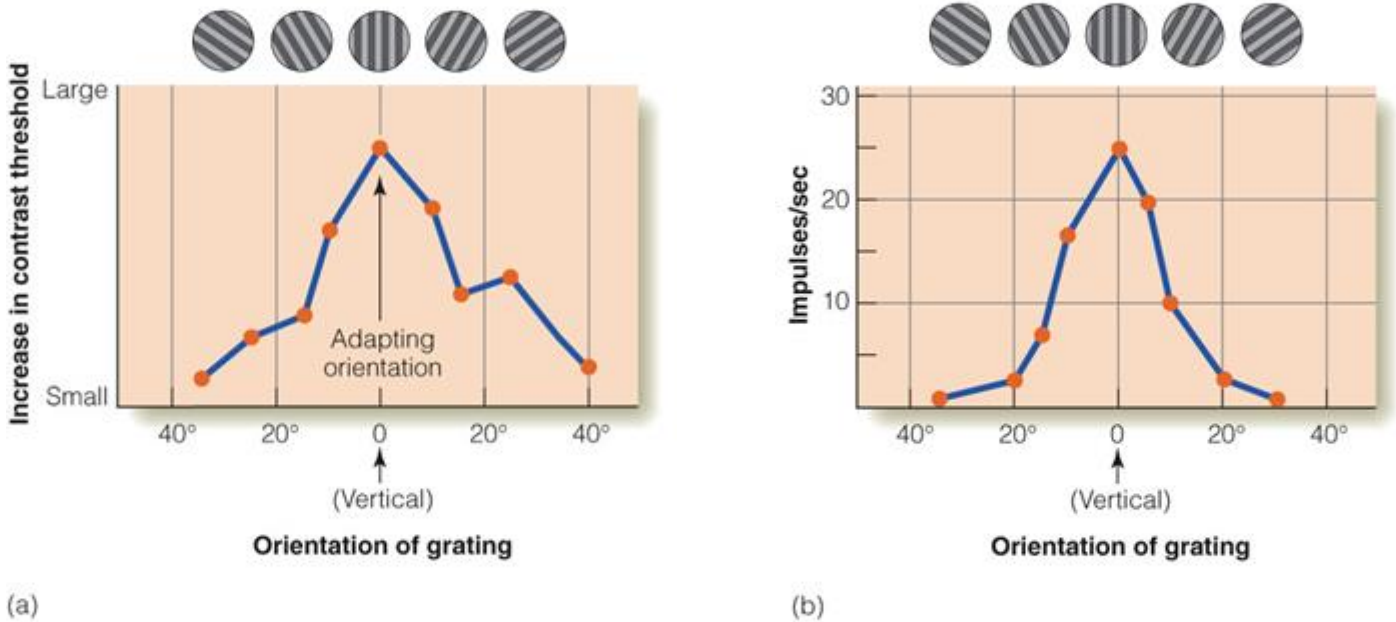
- Neurons tuned to specific stimuli (features) fatigue when exposure is long.

- Fatigue or **adaptation** to stimulus results in two main effects:
  - The neural firing rate will decrease.
  - The same neurons will fire less when a similar stimulus is immediately presented again.

- “Selective” means that only those neurons that respond to *the specific stimulus* will adapt (i.e. change firing rate).

Cell responses and perception

- Psychophysical curve should show selective adaptation for specific orientation if neurons are tuned to this characteristic.
- Recording from the same neuron (right) while responding to gratings of different orientations gives us a *tuning curve* for that cell.



Change in *perceptual* sensitivity (left) matches the selectivity of *neurons* (right).

Today

How (and why) do we perceive color?

- The importance of color
- Color basics – physical and perceptual
- The physiology of color vision
  - Trichromatic theory of color vision
  - Opponent-process theory
- Varieties of color vision

What does color vision do for us?

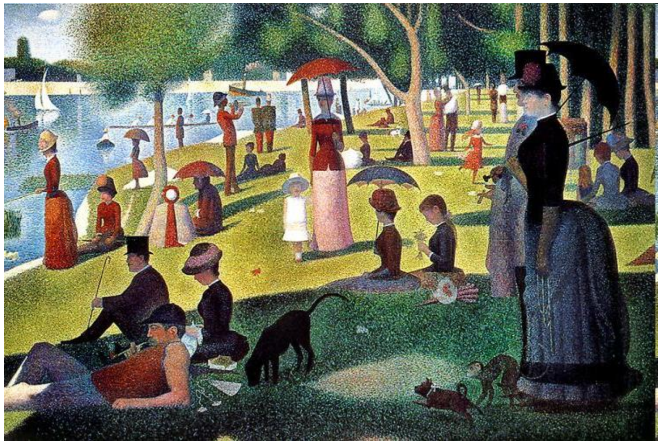
At the computational level (Marr's 1st level):

- Color is a visual feature that helps us classify and identify objects.
- Color facilitates perceptual organization of elements into objects. It can make some objects 'pop-out'.
- May provide an evolutionary advantage in foraging for food – especially calorie-packed fruits and berries.


Why is color vision important?

Color takes on meaning.

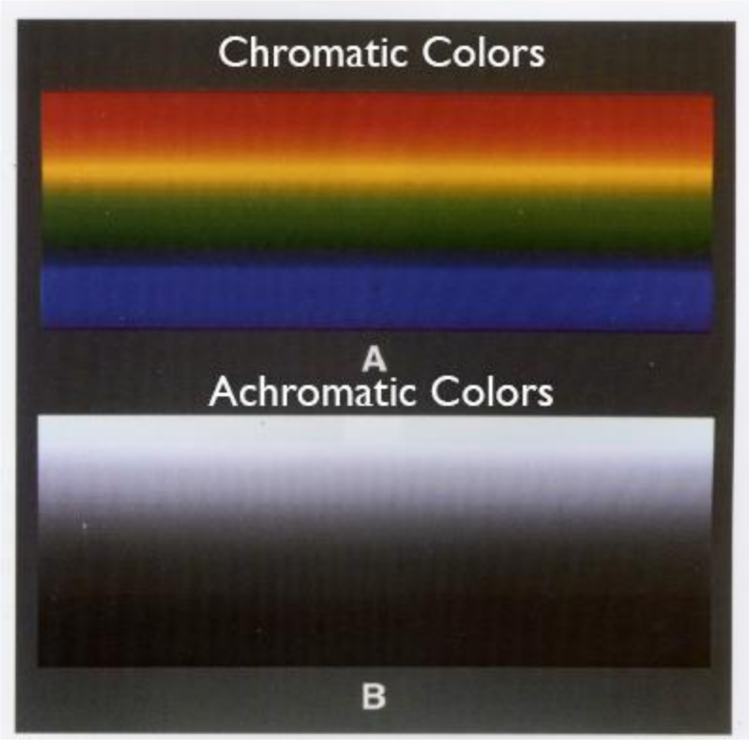
- We like color and have strong preferences.
- It affects our moods and performance. [Important in food, architecture, and UX design.]
- We assign it cultural significance (but the meaning isn't innate).



Georges Seurat

www.colormatters.com

What is color?



Physical basis of color

- Associated with our sensitivity to particular wavelengths in the electromagnetic spectrum.
- However, colors are *not* a property of light waves. Our experience of color is a result of an interaction with our sensory systems.
- When *particular* wavelengths reach our eyes, they can cause **chromatic colors** or **hues** to be perceived.
- If all wavelengths are transmitted equally, we see **achromatic color**.

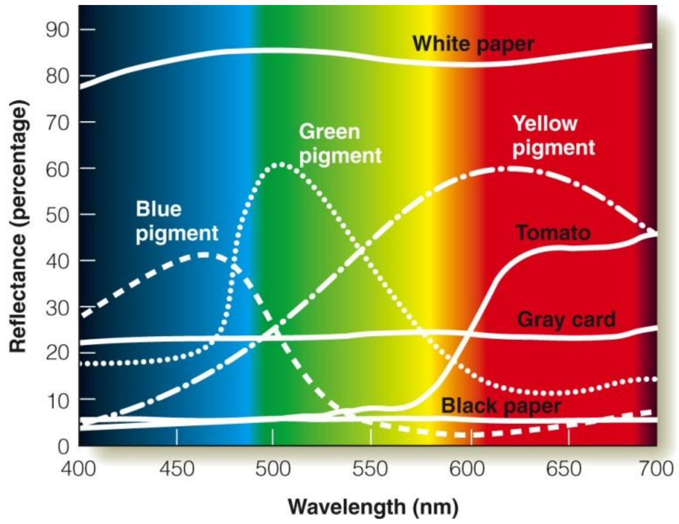
What is color?

Physical basis of color in objects

- The **selective reflectance** of an object specifies its chromatic color.
  - For *clear* objects, **selective transmission** specifies chromatic color.

- This can be expressed in a **reflectance curve**, plotting the percentage of photons reflected at each wavelength.

- Achromatic colors will reflect equal amounts of each wavelength, with the percentage reflectance determining brightness.



What colors do we perceive?

Four colors – red, yellow, green, and blue – are considered the '**basic colors**' (or 'psychological primaries').

- With these, we can describe our perception of any color.
- Color circle shows perceptual relationship among colors
- These four basic colors *correspond* to wavelengths of light reflected from an object. [We can discriminate about 200 colors based purely on wavelength.]
- However, some colors (e.g. brown) are extra-spectral and don't appear in the light color spectrum. They are the result of mixing two other colors.

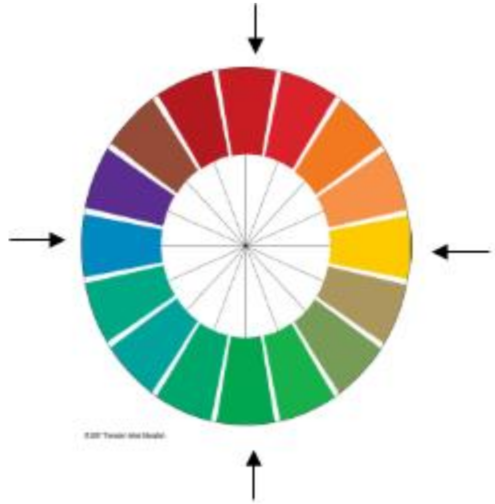


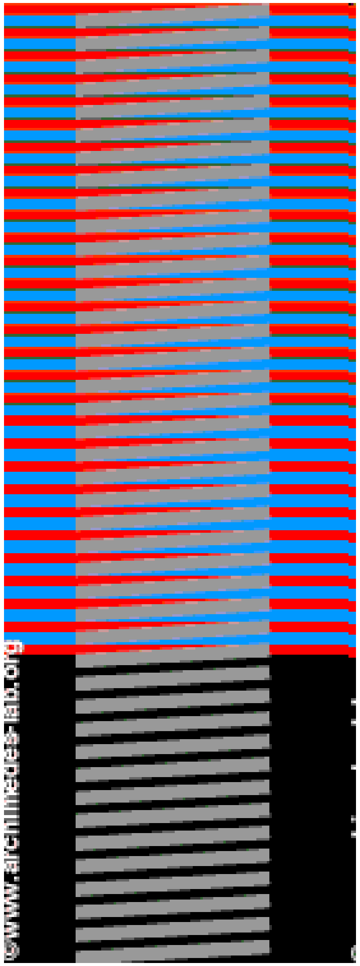
TABLE 9.1 | **Relationship Between Predominant Wavelengths Reflected and Color Perceived**

WAVELENGTHS REFLECTED	PERCEIVED COLOR
Short	Blue
Medium	Green
Long	Red
Long and medium	Yellow
Long, medium, and short	White

What affects our color perception?

Color perception can be changed by:

- **Intensity**: Changing the intensity of the light can make colors brighter or dimmer.
- **Saturation**: Adding white (with all wavelengths) to a specific color results in less saturated (desaturated) color, making it appear gray. Remove the white, and you get to a more ‘pure’ color as it has fewer competing wavelengths.
- **Simultaneous color contrast**: The background or surrounding colors of an object can alter the perceived colors. [Do the grey bars on the right look the same color?]



What affects our color perception?

Color perception can be changed by:

- Mixing colors to alter which wavelengths of light reach our eyes.
- The methods of doing this are **additive** color mixing and **subtractive** color mixing.

Color perception: Subtractive mixing

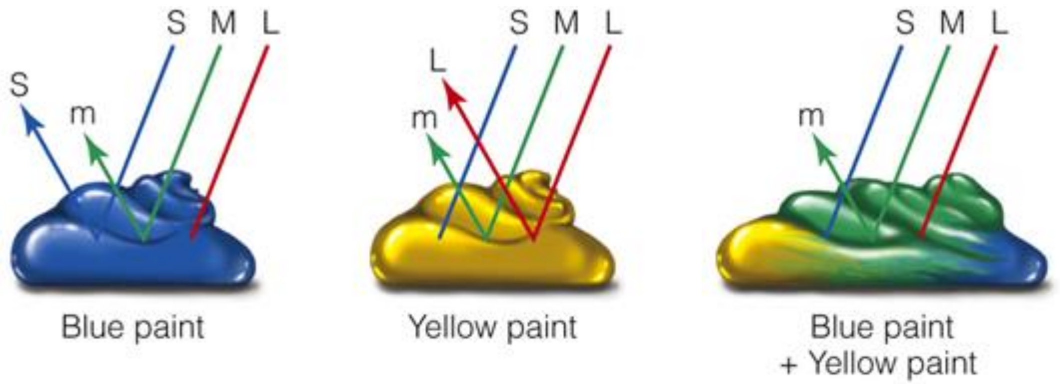
Subtractive color mixture:

- Mixing *paints* with different pigments.
- Additional pigments reflect *fewer* wavelengths, changing the **selective reflectance**.
- Mixing blue and yellow leads to green, because each pigment alone would reflect green.

TABLE 9.3 | Mixing Blue and Yellow Paints (Subtractive Color Mixture)

Parts of the spectrum that are absorbed and reflected by blue and yellow paint. Wavelengths that are reflected are highlighted for each paint. Light that is usually seen as green is the only light that is reflected in common by both paints.

	WAVELENGTHS		
	SHORT	MEDIUM	LONG
Blob of blue paint	Reflects all	Reflects some	Absorbs all
Blob of yellow paint	Absorbs all	Reflects some	Reflects some
Mixture of blue and yellow blobs	Absorbs all	Reflects some	Absorbs all



Color perception: Additive mixing

Additive color mixture:

- Mixing *lights* of different, specific wavelengths.
- All contributed wavelengths are available for the observer to see – direct combination of wavelengths
- Superimposing blue and yellow lights leads to white.

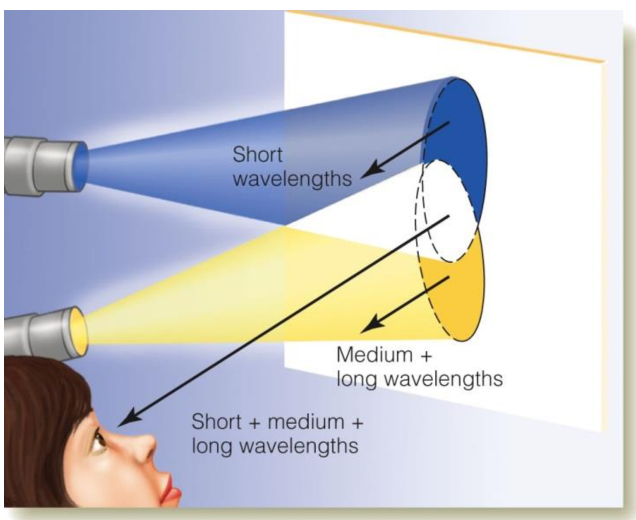


TABLE 9.2 **Mixing Blue and Yellow Lights (Additive Color Mixture)**

Parts of the spectrum that are reflected from a white surface for blue and yellow spots of light projected onto the surface. Wavelengths that are reflected are highlighted.

	WAVELENGTHS		
	SHORT	MEDIUM	LONG
Spot of blue light	Reflected	No Reflection	No Reflection
Spot of yellow light	No Reflection	Reflected	Reflected
Overlapping blue and yellow spots	Reflected	Reflected	Reflected

Page 202

Color perception

Progress check

In clear test tubes, you mix two different color liquids to produce a third (new) color. What kind of mixing is this?

A. Additive color mixing

B. Subtractive color mixing

Color perception

<u>Intuition check</u>

Based on what we know of additive and subtractive mixing, what is the minimum number of wavelengths of light you would need to mix to reproduce or match *any* given color?

A. 1

B. 2

C. 3

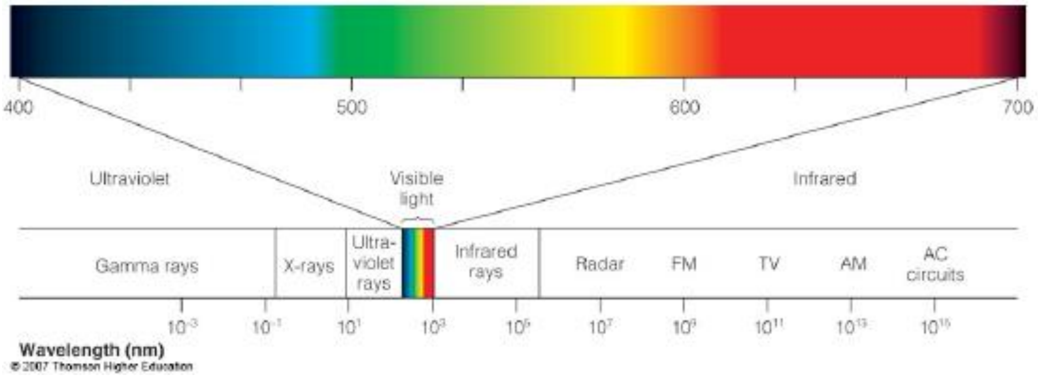
D. 4

E. I have no earthly idea

How do we see color?

How does the change in wavelengths received in the eye alter our perception of color?

- Color is not “contained” in the wavelength, but is certainly correlated with it.
- We need to build a physiological account, but with help from psychophysics and algorithmic models.



Theories of color vision

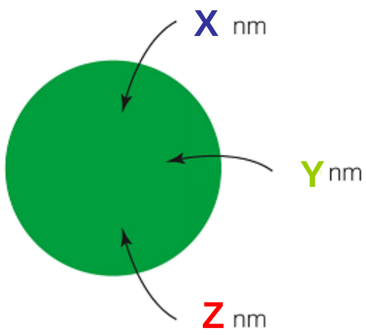
Trichromatic theory of color vision

- Proposed by Young and Helmholtz (1800s)
  - Suggested that **three** different receptor mechanisms are responsible for color vision.

- Based on psychophysical evidence
  - **Color-matching experiments**:

    Observers adjusted intensities of three wavelengths in a comparison field to match a test field of one wavelength.

Test field

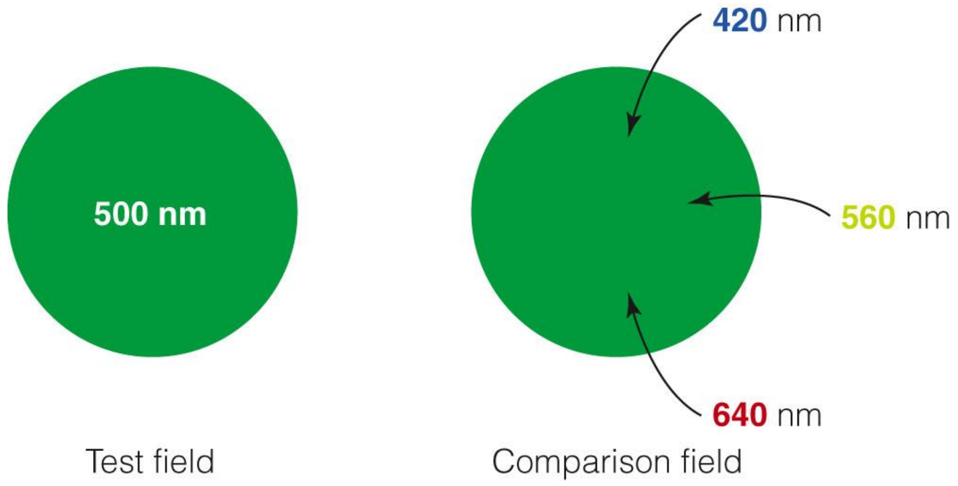


Comparison field

Trichromatic theory of color vision

Color-matching experiments:

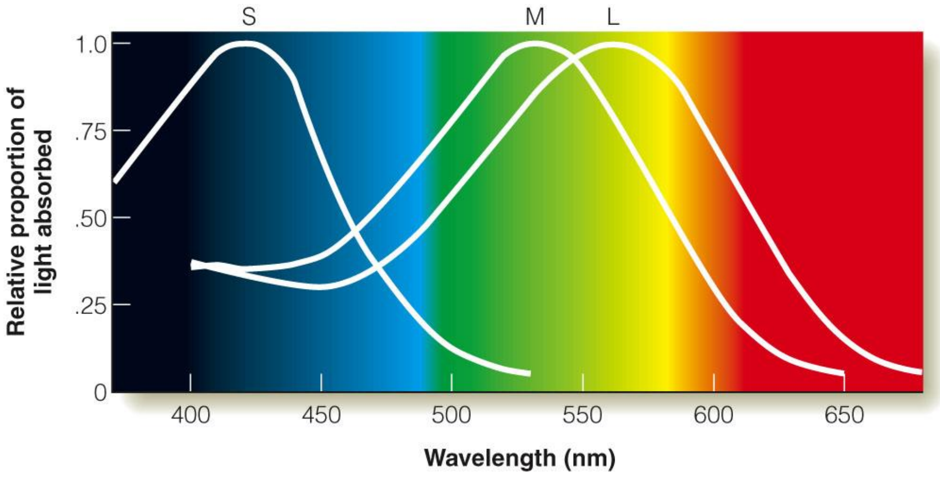
- Normal observers need *three wavelengths* of light to make the matches.
- Observers with *color deficiencies* can match colors by using only *two* wavelengths.
- Color matches based on different physical stimuli are called **metamers**.
- Strong evidence for the **trichromatic theory** and allows you to build a model and look for physiological (implementational) causes.



Trichromatic theory of color vision

- Researchers measured absorption spectra of visual pigments in receptors (1960s).
  - They found pigments that responded maximally to:
    - Short wavelengths (419nm)
    - Medium wavelengths (531nm)
    - Long wavelengths (558nm)
- Later researchers found genetic differences for coding proteins for the three pigments (1980s).

Short blue smurfs

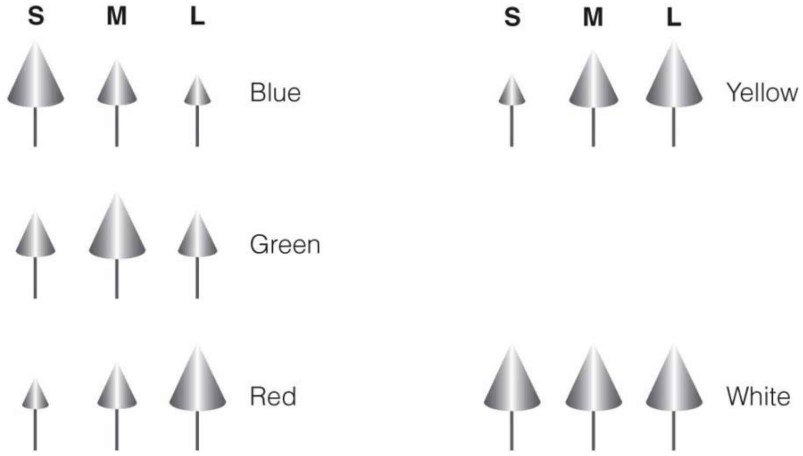


Long wavy red hair

Trichromatic theory of color vision

Color perception seems based on the responses of the three different types of cones.

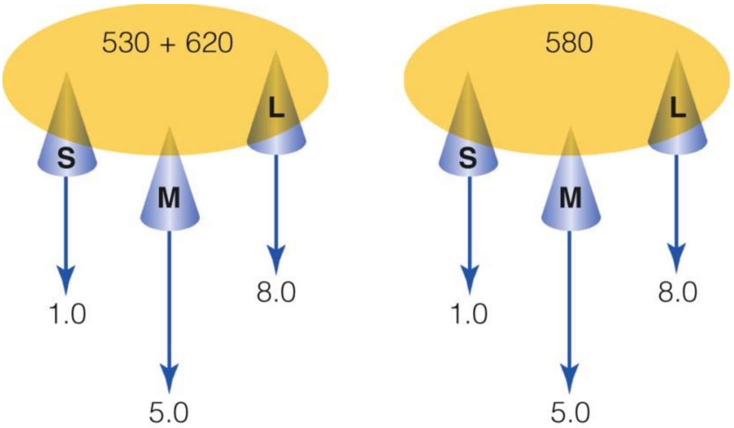
- Responses vary depending on the wavelengths available.
- Combinations of the responses across all three cone types lead to perception of all colors.
- Four basic colors represented: blue, green, red, and yellow



Trichromatic theory of color vision

The good news for trichromatic theory…

- Color matching experiments show that colors that are perceptually similar (metamers) can be caused by different physical wavelengths.
- **Metamers** are produced by different stimuli because they have indistinguishable firing patterns from color receptors.
- Physiological account supports psychophysical experiment.



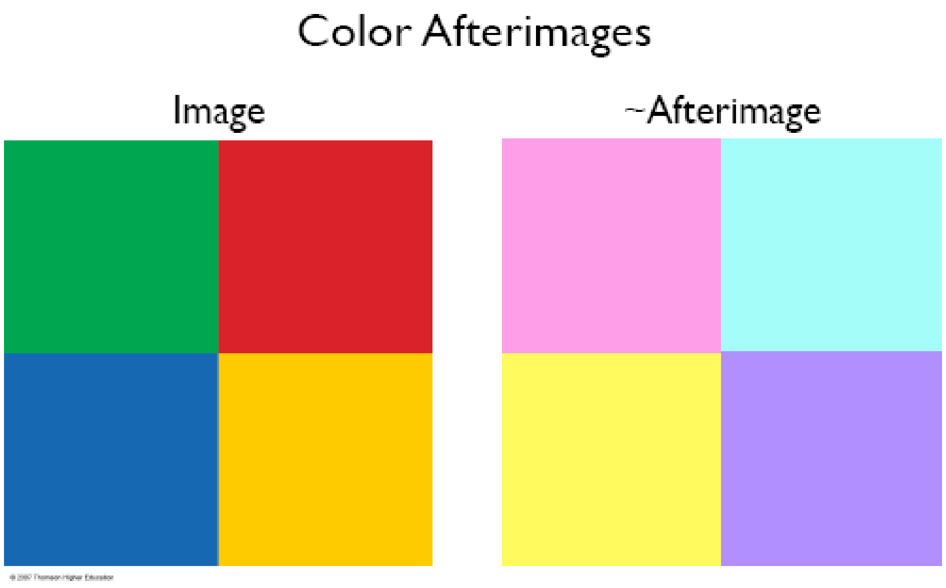
Competing theories of color vision

Though successful at explaining color matching experiments, the trichromatic theory was less helpful in giving a causal account of other phenomena.

Problematic observations included:

1. The fact that color blindness occurred in pairs of green/red and blue/yellow.
2. Individuals have difficultly in visualizing combinations of red and green, or blue and yellow.
3. Color **afterimages** have characteristic pairings: red after green adaptation, and blue after yellow adaptation.

What explains afterimages?

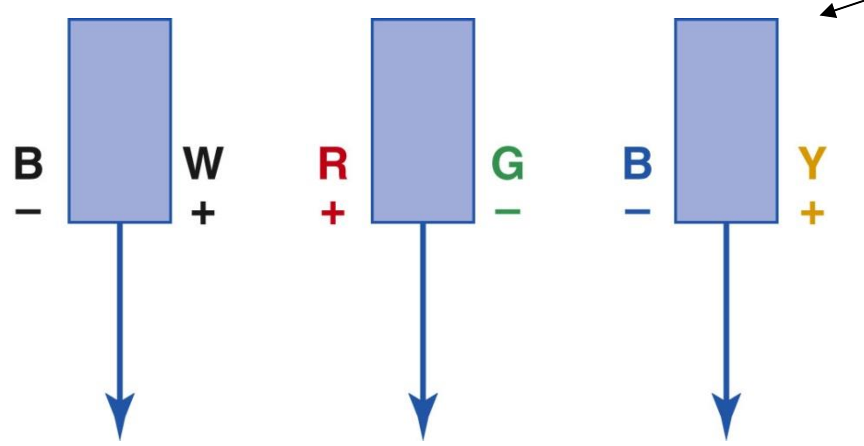


Consistent within individuals and between individuals with normal color vision.

Opponent-process theory

To account for these issues, Ewald Hering (1800s) suggested an **opponent-process theory** of color vision:

- Three proposed mechanisms process colors in pairs: red/green, blue/yellow, and white/black.
- The pairs respond in an opposing fashion, such as positively to red and negatively to green.
- These responses were believed to be the result of chemical reactions in the retina.

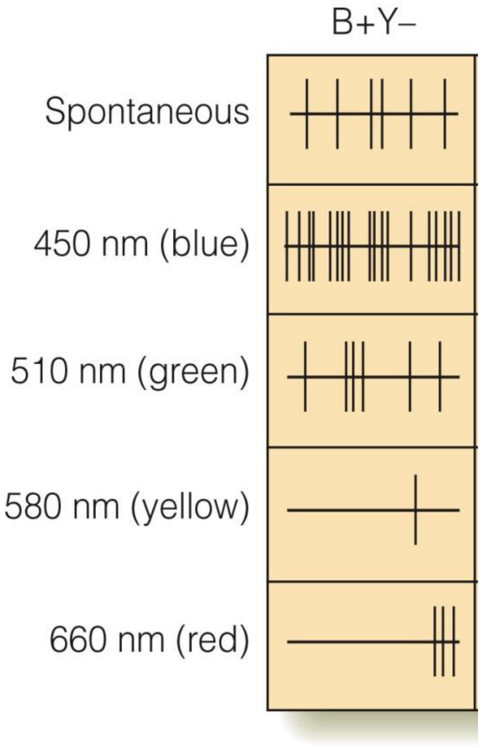


Lose one and you would be colorblind for both colors.

Opponent-process theory

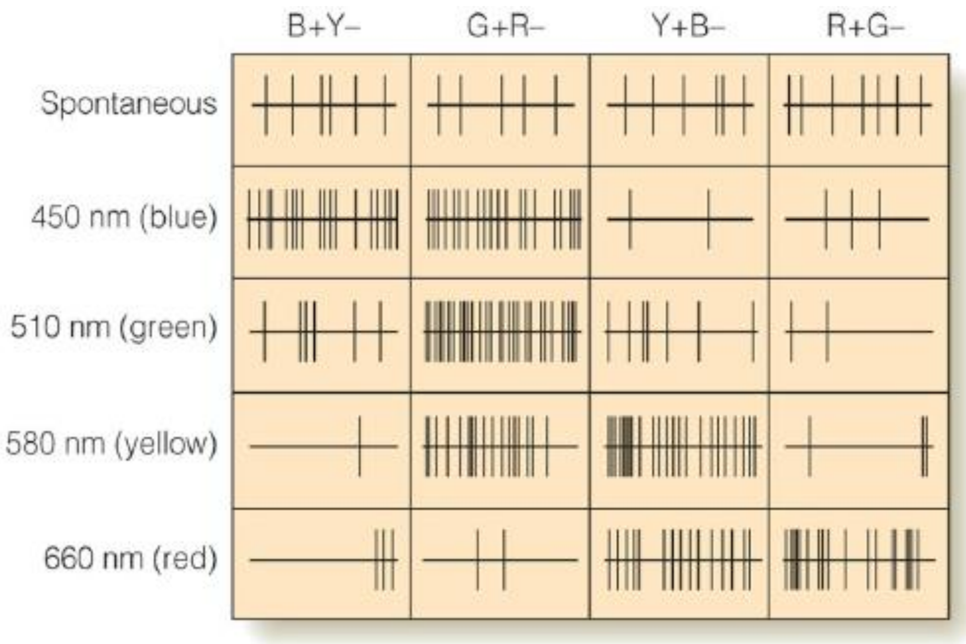
Researchers performing single-cell recordings found opponent neurons (1950s)

- Opponent neurons:
  - Are located in the retina, and LGN (parvocellular and koniocellular layers), and later in cortex.
  - Respond in an <u>excitatory</u> manner to one range of wavelengths and in an *inhibitory* manner to other specific wavelengths.



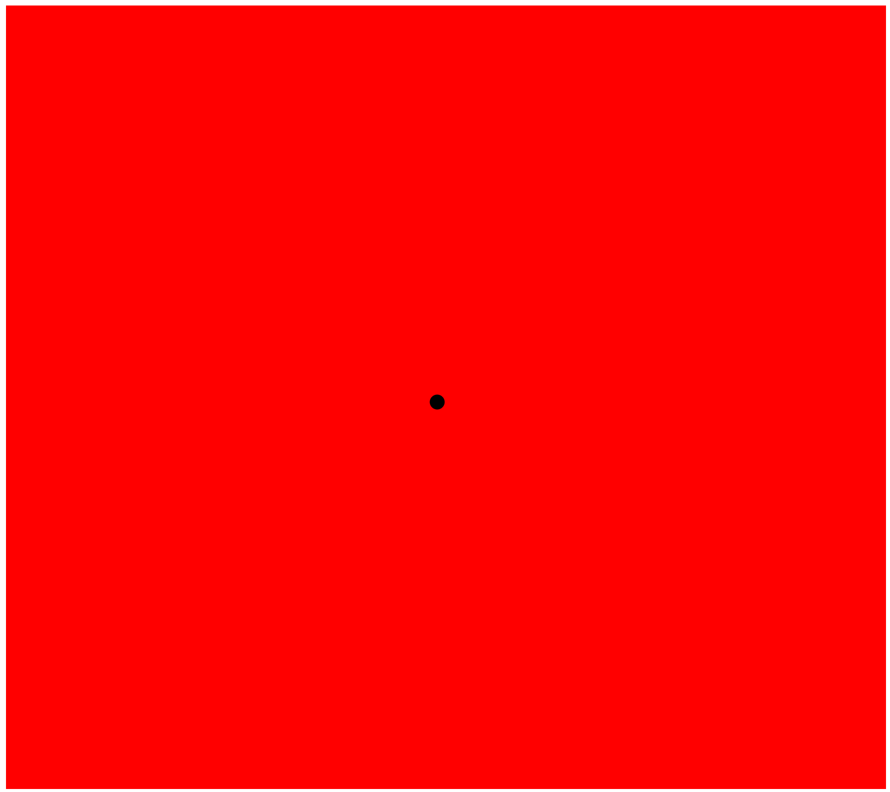
Opponent-process theory

The discovery of opponent firing cells supported the opponent-process theory, but slightly changed the proposed types of opponent cells.



Color adaptation

Stare at the center of the red square



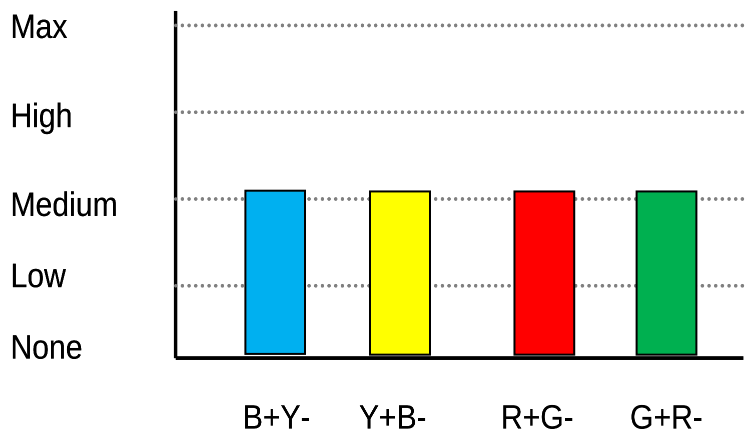
Color adaptation

Now what do you see?

Color adaptation

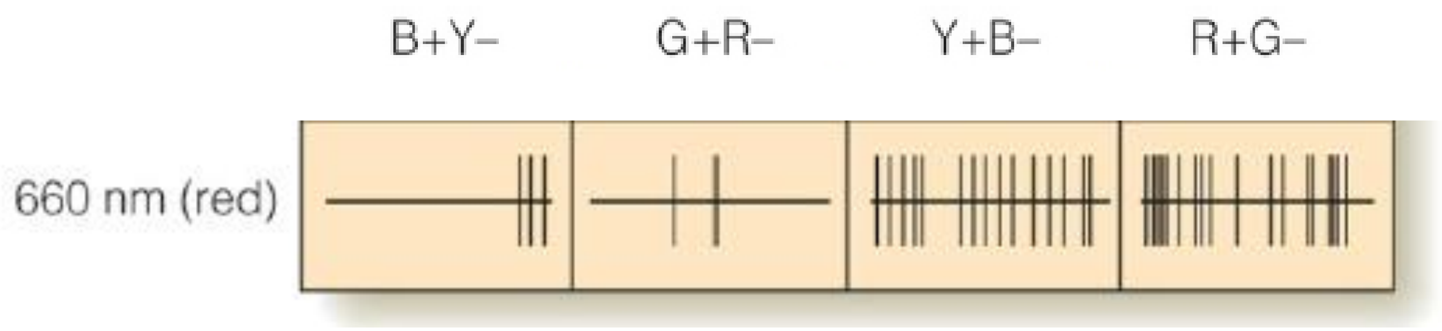
Opponent-process theory explanation

Opponent cells responding to white light, before any adaptation occurs.



Color adaptation

While adapting to red, these are the neural firing patterns:

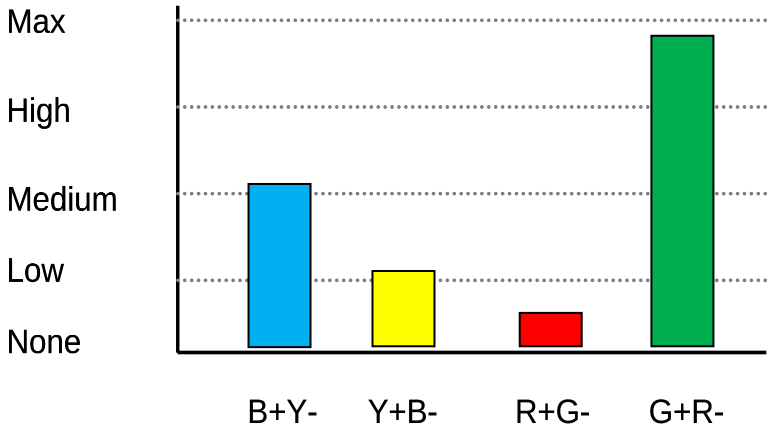


Inhibit! excite… **Excite!!!**

Color adaptation

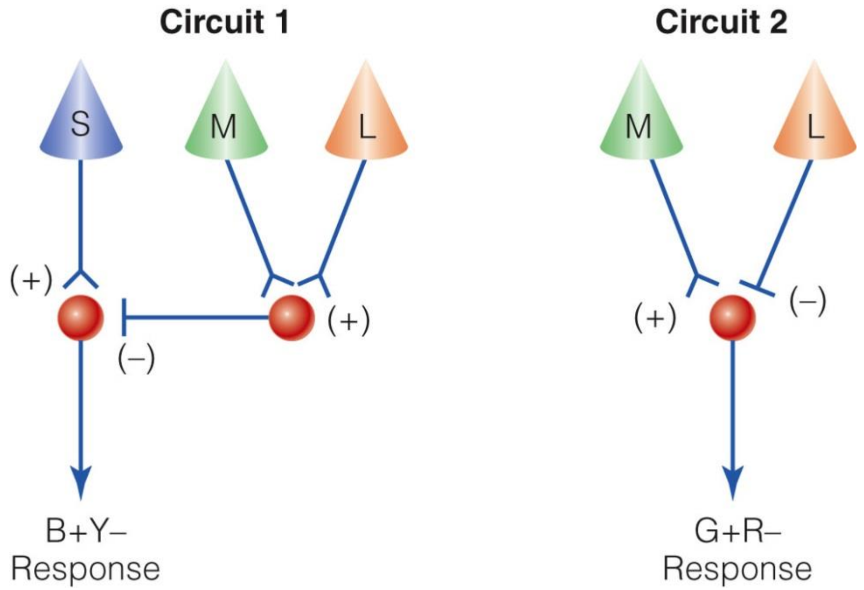
Opponent-process theory explanation

When you finish adapting to red and go back to a white background, the R+G- and Y+B- will be fatigued and fire less. The G+R- will rebound from inhibition and fire more.



How does the brain implement opponent cells?

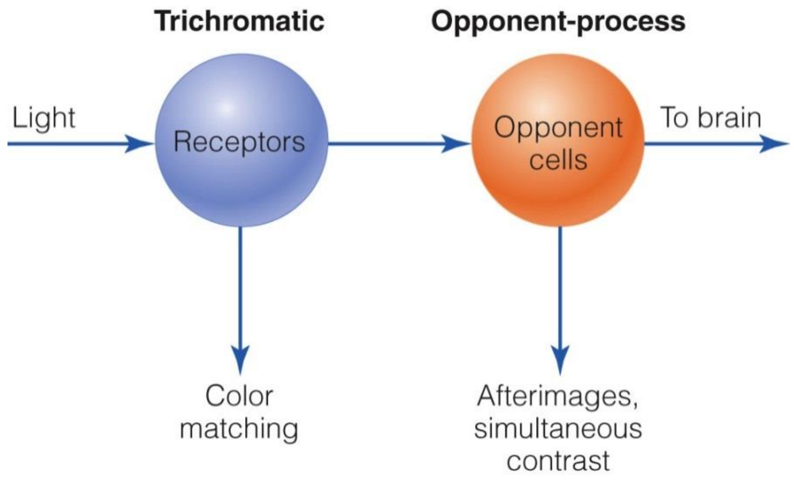
Simple neural circuits can be constructed from receptors in the retina to form the opponent neurons



Color vision theories

Compatible theories?

- Each theory describes physiological mechanisms in the visual system
  - Trichromatic theory explains the responses of the cones in the retina.
  - Opponent-process theory explains neural response for cells with those cones in their receptive fields. These signals affect activity in retina, LGN and cortex.



Color vision

If color detection and mixing occur in the retina, where does color perception take place in the brain?

There is no single module for color perception

- Color is ‘created’ by the interaction of many brain areas. This is an example of distributed processing (as opposed to specificity coding).
- Cortical cells in V1, V2, and V4 respond to some wavelengths or have opponent responses.
- These cells usually also respond to forms and orientations.
- Cortical cells that respond to color may also respond to white.
- Yet, damage to some areas (like V4), can result in **cerebral achromatopsia** – an inability to perceive color.

Color vision theories

Progress check

After adapting to a blue square, if you look at a white space you will see a ________ afterimage. This phenomenon is explained best by the ________________ color theory.

A. green, opponent-process

B. yellow, trichromatic

C. red, trichromatic

D. yellow, opponent-process

E. green, opponent-process

Varieties of color vision

Now that we have a general theory of color that works on procedural (**algorithmic**) and concrete (**implementation**) levels, we can start to predict some of the possible differences and failure modes in color vision.

We can ask: why do we need so many cones and what happens if we don't have them?

Varieties of color vision

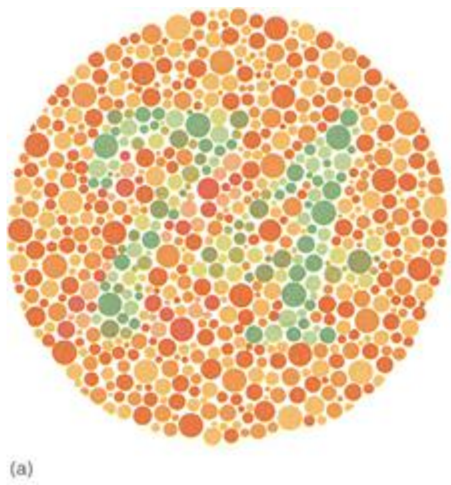
As we saw earlier, color deficiencies in human vision can be tested in color matching experiments:

- **Monochromat** - Needs only one wavelength to match any color.
- **Dichromat** - Needs only two wavelengths to match any color. Most common color deficiency in humans.
- **Anomalous trichromat** - Needs three wavelengths in different proportions than normal trichromat.
- **Unilateral dichromat** - Trichromatic vision in one eye and dichromatic in other.
- Some people may be *tetrachromats* – having more than three cone receptors.

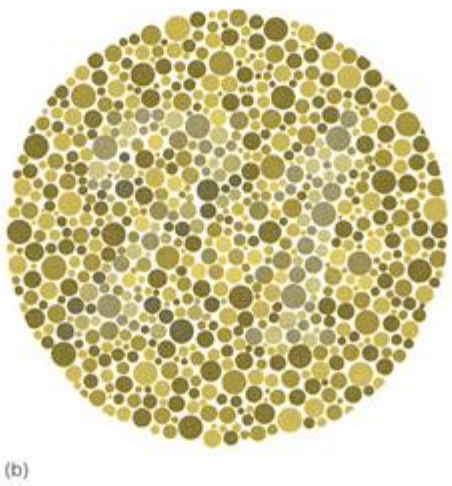
[See page 209.]

Varieties of color vision

Ishihara plates can also test for color perception deficiency.



Normal trichromat



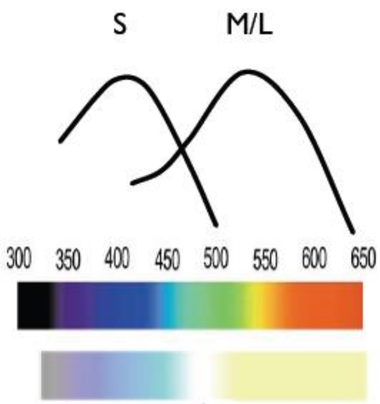
Red/green protanope (dichromat)

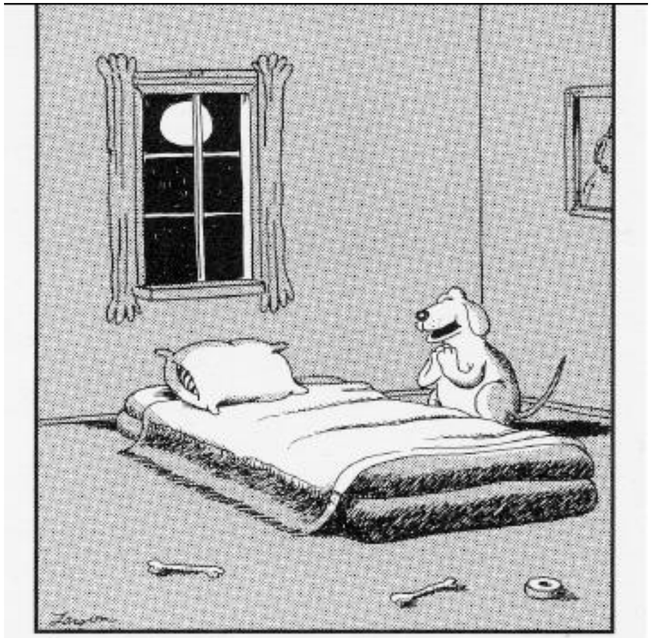
Other varieties of color vision

Are dogs (and cats) color blind?

- They are actually dichromats and have 2 color sensitive receptors.
- Most mammals seem to be **color deficient**.

Dichromatic: Two cones





"...And please let Mom, Dad, Rex, Ginger, Tucker, me, and all the rest of the family see color."

Other varieties of color vision

Beyond 4 receptors

- The mantis shrimp is said to have up to 16 photopigments.
- This helps them hunt, navigate (on coral), avoid predators, and select mates.

Next time

- Midterm 1
- Start chapter 5 afterwards