NAME ______________________________ DATE ______________

Handout 1:
Color Survey

Have you ever thought about whether everyone sees colors in the same way?
Here's your chance to find out!

Your teacher will display crayons or slides. Categorize each of the 15 colors under *one* of the six major color headings in the table below. If a crayon or slide doesn't seem to fit well under any of the categories, choose the category that seems best.

Color Categories						
	Red	**Orange**	**Yellow**	**Green**	**Blue**	**Violet**
Color 1						
Color 2						
Color 3						
Color 4						
Color 5						
Color 6						
Color 7						
Color 8						
Color 9						
Color 10						
Color 11						
Color 12						
Color 13						
Color 14						
Color 15						

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Handout 2: Unit Overview

Light! Color! Perception!

How do we perceive color? Is my red *the same as your* red*? How about my* blue*? Do all human beings perceive color in the same way?*

Surprisingly, no. A large number of factors affect your perception of a color, including light, other colors next to it, and your own eyes and brain. As you explore how human beings and other animals perceive color, you will develop a deeper understanding of how the nervous system transmits and interprets information from the environment.

You'll begin each area of investigation by experiencing a visual illusion (an image that tricks your eyes and brain). Then, using your own observations as a starting point, you will explore, in turn, the relationship of color and light, the physiology*—biological workings—of the eye, and the way the eye and brain interact with light to create your perception of color. Finally, you will experience how arts and media use color to produce a range of visual effects.*

As you carry out the unit activities, you will look for answers to the following questions:

- *How do the eye and brain work together in the nervous system to perceive color?*
- *How do arts and media take advantage of eye and brain interactions to produce visual effects?*

What You Will Do in This Unit

Experience mystifying illusions. Experience a series of visual illusions and ask questions about what causes them.

Diagram the human eye. Learn what really happens in the eye and brain when you see colors.

Find out why blue and yellow don't always make green. Try two forms of color mixing that produce different results and understand their origins in biology.

Explore visual effects in art. Explore the perceptual tricks used by arts and the media and explain why they work.

Vocabulary Used in This Unit

Additive mixing: Mixing of colored light, in which wavelengths are added together.

Complementary contrast: Phenomenon in which the juxtaposition of *complementary colors*—colors opposite one another on the color wheel—make each color appear brighter and stronger.

Cones: Photoreceptors in the eye that respond to color, particularly in bright conditions.

Dichromacy: Condition in which a person has only two types of functioning cones and therefore cannot perceive some of the wavelengths of light.

Electromagnetic spectrum: Range of radiation that includes, in addition to visible light, radio waves of all kinds, infrared radiation, ultraviolet radiation, X-ray, and gamma ray radiation.

Equiluminance: Phenomenon in which two colors of equal brightness placed next to each other appear to float or vibrate.

Frequency: Number of waves (measured by successive crests) that pass by a point in space in a certain unit of time (often measured "per second").

Illusion: A false perception of reality; something presented in a way that causes viewers to misinterpret what they see and to perceive it as different from the way it really is.

Monochromat: Person who has only one type of functioning cone.

Nanometer: A unit of measurement equal to a billionth of a meter (abbreviated *nm*).

Neurons: Cells that process and transmit information through electrochemical impulses. Neurons, also known as nerve cells, are the primary component of the nervous system.

Opponency: Theory that states that certain pairs of colors—red and green; yellow and blue—are mutually exclusive. That is, there are no reddish greens or bluish yellows.

Partitive mixing: Type of color mixing in which colors are presented as very small discrete dots, or parts, arranged close to one another, so that the colors are mixed in the viewer's eye. The painting style *pointillism* relies on partitive mixing, as do the printing process and computer monitors.

Perception: A body's response to a stimulus in the environment. Living things perceive the world through their senses.

Photoreceptor: A nerve cell or group of cells located on the retina and specialized to sense or receive light.

Pointillism: Style of painting in which small dots of pure color are placed close to one another.

Response: Function or activity displayed by an organism or part of an organism when activated or excited.

Rods: Photoreceptors in the eye that respond to brightness, but not color. Rods function in low-light conditions.

Simultaneous contrast: Phenomenon in which the juxtaposition of two different colors affects our perception of each color's hue.

Stimulus: Something in the environment that excites an organism or a part of an organism to respond or function.

Subtractive mixing: Mixing of colored pigments, in which certain wavelengths of light are absorbed and others are reflected.

Trichromacy: The theory that any color can be produced using combinations of three primary colors.

Wavelength: The distance between a point on one wave and the same point on the next wave, usually measured between successive *crests* (high points) or *troughs* (low points).

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Assessment Checklist:
Color Perception

Use the table below to help you complete your final assessment. Make sure to include all the requirements. Your teacher will use this assessment to evaluate your work.

Requirements	Percentage of Total Grade	Comments	
Color Perception Assessment		**Student Comments**	**Teacher Comments**
Summarize what color is and how the nervous system faciliates color perception, including: • The relationship of light to color (20%) • The structure of the eye and the function of its parts, including lens, retina, and photoreceptors (30%) • The role of the brain in receiving and interpreting visual information (20%)	**70%**		
For a chosen example of an artwork, illusion, or media piece that uses a color effect covered in this unit: • Identify or name the effect (5%) • Describe what you perceive (5%) • Explain how the interactions of light, eye, and brain through the nervous system create the perception (10%) • Illustrate your explanation with a diagram comprising the example work, light, the eye, and the brain (10%)	**30%**		
Total	**100%**		

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Handout 3:
Illusion 1: Gray or White?

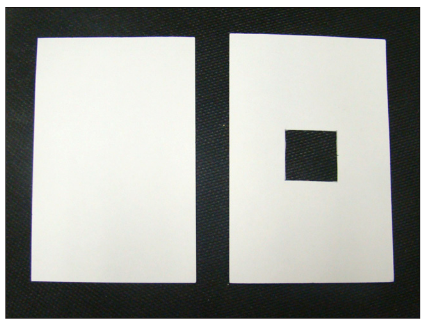
In this illusion, you will watch two cards *change color*!

Procedure

Perform the following steps with your partner:

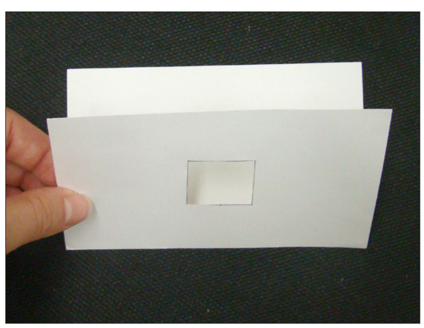
1. Cut a 1-inch square hole in the center of one index card.

2. Place the uncut index card on the windowsill or on a table under a light source. Place the index card with the cut-out square hole beside it.



What colors are the cards?

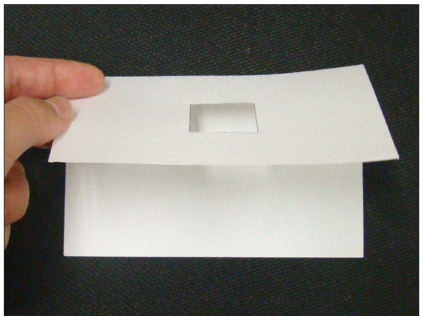
3. Now place the cut card directly above on top of the solid card. Then lift and tilt the cut card toward the light.



What color is the solid card seen through the hole in the cut card?

What color is the cut card?

4. Lay the cut card on top of the solid card again. Then lift and tilt the cut card away from the light. Look at the solid card through the square hole.



What color is the solid card?

What color is the cut card?

Think about how your perceptions of card color changed. Based on your observations, what question(s) would you like to have answered?

Handout 4:
Light and Color

Newton's Discoveries

In 1665, Isaac Newton made a groundbreaking discovery about the nature of light. By allowing a sunbeam to pass through a triangular piece of glass (a prism), he demonstrated that the prism divided the white light into various colors. Although Newton saw a progression of gradually changing colors, or gradations, he named seven colors, choosing the number seven to correspond with the seven notes of a musical scale.

Newton described the colors with the names Red, Orange, Yellow, Green, Blue, Indigo, and Violet, which you might remember now by the mnemonic "Roy G. Biv."

In further experimentation, Newton also demonstrated the following:

- The arrangement of the colors in the separated spectrum was always the same.
- Once colors had been separated with the prism, they could not be separated further.
- The separated colors could be "put back together" to yield white light when passed through a second prism.

Newton hypothesized that there was a physical property of light that corresponded to each spectral color, causing each color to bend at a different angle through the prism.

Light as a Wave

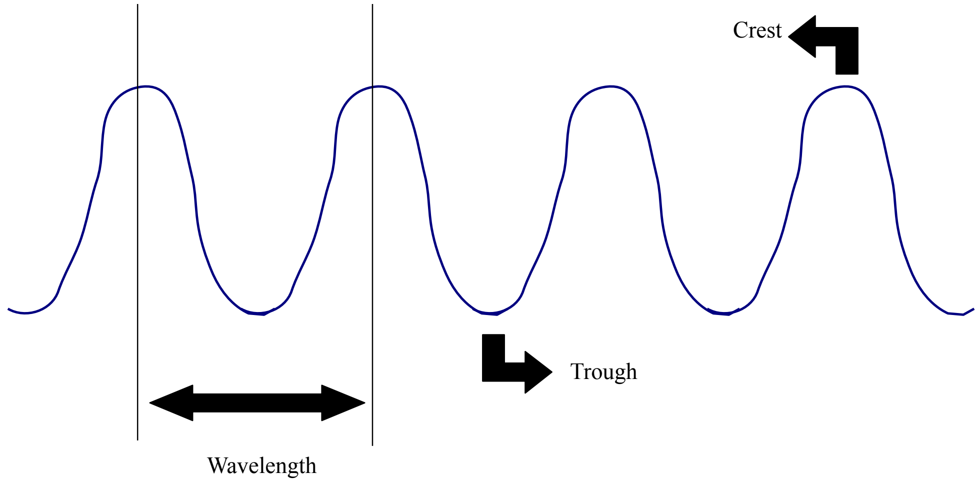
Scientists later determined that light can be separated by shining it through a prism because light behaves as a wave, bending when it passes through materials in which light speed varies.

The color spectrum that Newton observed is the visible part of a larger spectrum, called the *electromagnetic spectrum*. The electromagnetic spectrum also includes radio waves, infrared radiation, ultraviolet radiation, X-ray, and gamma ray radiation.

The two most important properties of waves with respect to the behavior of light are *wavelength* and *frequency*.

Wavelength is the distance between a point on one wave and the same point on the next wave, usually measured between successive *crests* (high points) or *troughs* (low points).

The diagram below is a representation of a wave, showing these features.

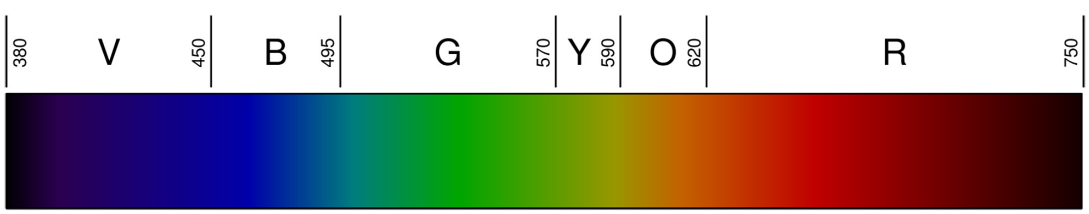


Frequency is the number of waves that pass by a point in space in a certain unit of time (often measured "per second").

The distance between two successive crests in the visible spectrum is very small, around 500 billionths of a meter. A billionth of a meter is known as a *nanometer*, abbreviated *nm*.

Our eyes can only detect light in the range of 380 to 760 nanometers. An object that does not emit light appears to be a certain color because the object absorbs certain wavelengths of visible light and reflects other wavelengths. The reflected wavelengths determine the colors we see.

The graphic below shows the ranges, in nanometers, of the spectral colors in the visible spectrum. This spectrum is similar to what Newton observed in his prism experiments. Note that this spectrum does not show a wavelength range for indigo, as most people today do not categorize indigo as a separate color, but rather see it as a shade of blue.



NAME **DATE**

Questions

- Where might you have observed a color spectrum similar to the one produced by Newton?
- What would be the approximate wavelength of a wave with the spectral color red?
- What color is a wave with a wavelength of approximately 450 *nm*?
- When you look at a green object, what color is being reflected?
- What colors of light does a white object reflect?

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Handout 5:
Viewing Objects with Colored Light

In this activity, you will shine different-colored lights on different-colored objects and observe the effects of colored light on your perception of an object's color.

With your group, collect these materials:

- Red, blue, and green objects (1 of each)
- Four flashlights
- Red, blue, and green colored filters
- Rubber bands or cellophane tape

Procedure

1. Write the names of your three objects in the table below.
2. Predict the color of each object when viewed under each color of light. Fill in the "Predicted Color" column for each object under each color of light.
3. Shine the flashlight with the white beam on each of the three objects. What color do you perceive for each object? Record your observations in the table.
4. Attach the color filters to the flashlights and shine each flashlight on each object. What colors do you perceive? Record your observations in the table.
5. What do you conclude about your changing color perception?

Object	**Color of Light**	**Predicted Color**	**Perceived Color**
Object 1: ______________ (Red object)	White		
	Red		
	Blue		
	Green		
Object 2: ______________ (Blue object)	White		
	Red		
	Blue		
	Green		
Object 3: ______________ (Green object)	White		
	Red		
	Blue		
	Green		

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Handout 6:
Illusion 2: After-Images

In this illusion, you will perceive colors that are not actually there!

Procedure

Stare at the bright red paper square continuously for about 30 seconds. Then look at the sheet of plain white paper.

What do you see?

Now try the same procedure with the bright blue paper square. What do you see?

The different colors you see on the sheet of white paper are called *after-images*.

What do you see when you stare at a bright light or a camera flash and then look away?

Think about what you have observed. Come up with a question or two about after-images that you would like to have answered.

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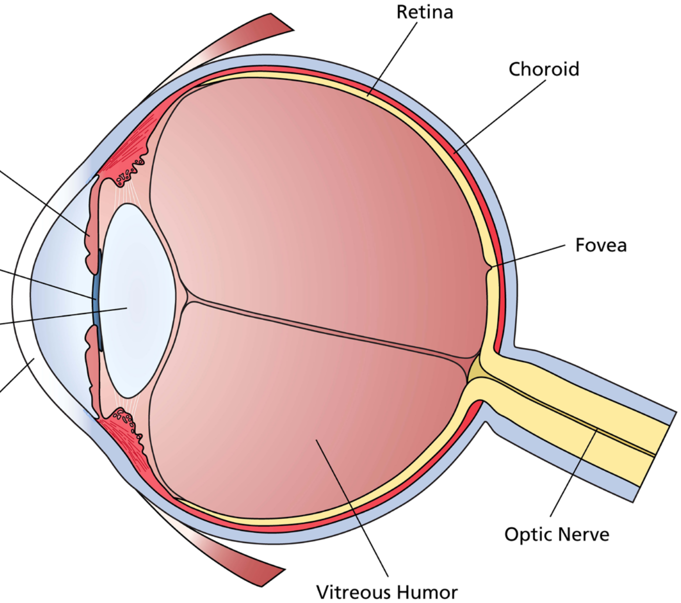
Handout 7:
The Eye



Parts of the Eye

Choroid: Layer of blood vessels that nourishes the eye; also acts as a light-absorbing layer.

Cornea: Transparent tissue covering the front of the eye; has nerves but no blood vessels.

Fovea: Small indent in the surface of the retina, where the majority of light that comes into the eye is focused.

Iris: Circular band of muscles that control the size of the pupil. The pigmentation of the iris gives "color" to the eye. Blue eyes have the least pigment; brown eyes, the most.

Lens: Transparent tissue that bends light passing through the eye. To focus light, the lens can change shape by bending.

Optic nerve: The complex web of nerve fibers that transmits information in the form of electrochemical impulses from the retina to the brain.

Pupil: The circular opening in the center of the iris of the eye, through which light passes to the retina. The pupil determines how much light is let into the eye.

Retina: Layer of tissue on the back portion of the eye that contains cells responsive to light (photoreceptors).

Vitreous humor: Clear, jelly-like fluid found in the back portion of the eye, which maintains the shape of the eye.

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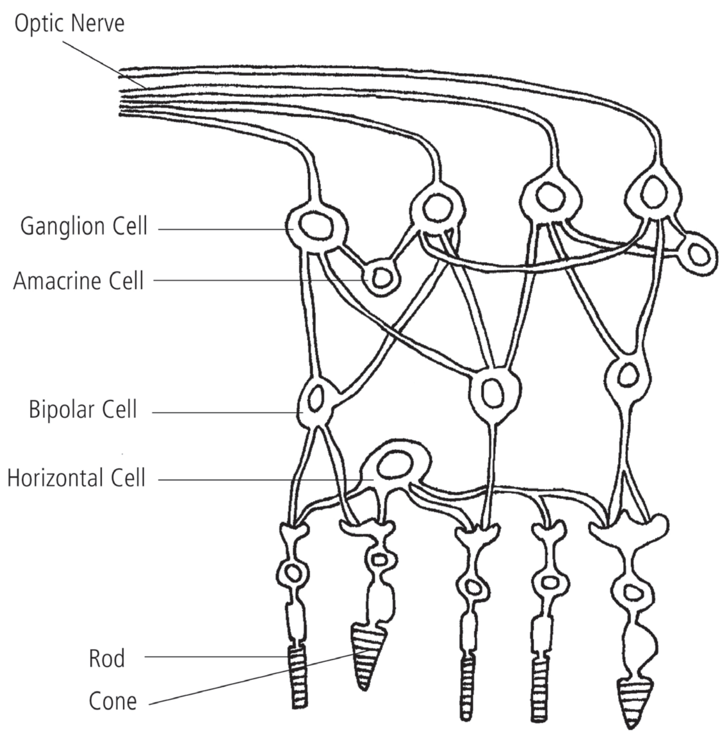
What Happens When You See?

When a person "sees," light enters through the clear *cornea* and *lens* at the front of the eye. The eye itself is filled with the transparent *vitreous humor*. The lens is suspended in the vitreous humor and held in place with a system of muscles. The shape of the lens is unconsciously controlled by these muscles. When rays of light pass through the cornea and lens, the rays bend, focusing an upside-down image on the *retina*, a layer of light-sensitive nerve cells at the back of the eye. The retina is part of the central nervous system.

The most important part of the retina is the *fovea*, a small indent in the surface of the retina. When a person wants to see something in very sharp focus, such as when threading a needle, the lens muscles move to allow the lens to project the image into the middle of the fovea. The majority of the light that comes into the eye is focused on the fovea.

The retina has multiple layers and is covered in about 120 million light-sensitive cells, called *photoreceptors*. There are two types of photoreceptors, called *rods* and *cones*, based on their shapes. About 7 million photoreceptors are cones and the rest are rods. Information about light stimuli received by rods and cones is transmitted to the brain through a complex of nerve cells, or *neurons*—bipolar cells, amacrine cells, and horizontal cells—as shown in the diagram of retinal layers below. These neurons in turn feed into ganglion cells, which come together in the optic nerve to transport light signals to the brain.



Photoreceptors on the Retina

In bright light, color-sensitive cones are responsible for vision. But in dim light, rods are more sensitive to patterns of brightness—in fact, rods are what allow people and animals to see in the dark. When the environment changes from light to dark, cones shut down and rods take over. Although rods can sense very low levels of light, they are "colorblind." Consequently, you are unable to distinguish color in dim light.

Rods and cones are not distributed evenly across the retina. Cones are most densely concentrated at the main point of the eye's focus, the fovea. Because of this, the fovea is most sensitive to color.

Rods are absent from the fovea, but moving outward from the center of the retina, the number of cones decreases and the number of rods increases. On the edge of the retina, there are no cones, only rods.

Human Cones and Color

You have learned that different colors of light correspond to different wavelengths on the electromagnetic spectrum. Your cones are able to perceive color because they are sensitive to different wavelengths of light.

You have three types of cones in your retina. Each type is particularly sensitive to a range of wavelengths, which correspond to different colors in the spectrum:

1. ***S*** cones, or short wavelength cones, are most sensitive to blues, colors with the shortest wavelengths.
2. ***M*** cones, or medium wavelength cones, are most sensitive to greens, colors of medium wavelength.
3. ***L*** cones, or long wavelength cones, are most sensitive to reds, colors with the longest wavelength.

Each type of cone is not stimulated exclusively by light wavelengths in its most sensitive range, but each is more sensitive to those wavelengths than to others. When the three types of cones are activated to greater or lesser degrees and in different combinations by light stimuli in the environment, human beings can perceive up to 9 million colors.

People who are colorblind usually possess fewer than three types of cones. *Dichromacy* refers to a condition in which a person has only two types of cones and therefore cannot perceive all wavelengths of light. A *monochromat* has only one type of functioning cone.

The three colors associated with the three types of cones—blue, green, and red—are sometimes called "eye primaries."

Cones in the Animal World

Early mammals had only one type of cone—***S*** cones—so they could perceive only blues and greens. The next evolutionary step in color vision was the development of a second kind of cone, which increased the range of wavelength to which the eye was sensitized, thereby increasing color vision, an adaptation that helped the survival of certain animal species.

The distribution of color vision in animals might surprise you. Among mammals, only the higher primates, including gorillas and chimpanzees, have three cones, and thus the same range of color vision that humans do. Most non-primate mammals have only two types of cones. Dogs are particularly sensitive to blue and violet colors.

Insects, however, have three cones, and some, like bees, can detect ultraviolet light. And birds have been found to have *four* cones—so they can see colors we can't see!

Sharks have no cones at all and so can't perceive color. Sea turtles, adapted to live in the deep ocean, have red oil droplets in their cones, which filter out short wavelengths. They can see reds, oranges, and yellows, but not greens, blues, and violets.

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What Do You Think?

1. Using what you now know about rods and cones, can you explain what might be happening when your eyes “adjust” to the dark?

2. If a person had ***L*** cones and ***M*** cones but no ***S*** cones, what color would that person *not* be able to see?

3. Why do you think the three colors, red, green, and blue, are sometimes called “eye primaries”?

4. Most mammals do not have the range of color vision that humans have. Think about when most mammals are active in the wild. Why might color vision be less important for them? What types of photoreceptors might be most important?

5. Why might having red oil droplets in their cones be a helpful adaptation for sea turtles?

6. Why might knowing how our eyes and brains react to the stimuli of different colors be useful for an artist or someone working in the media?

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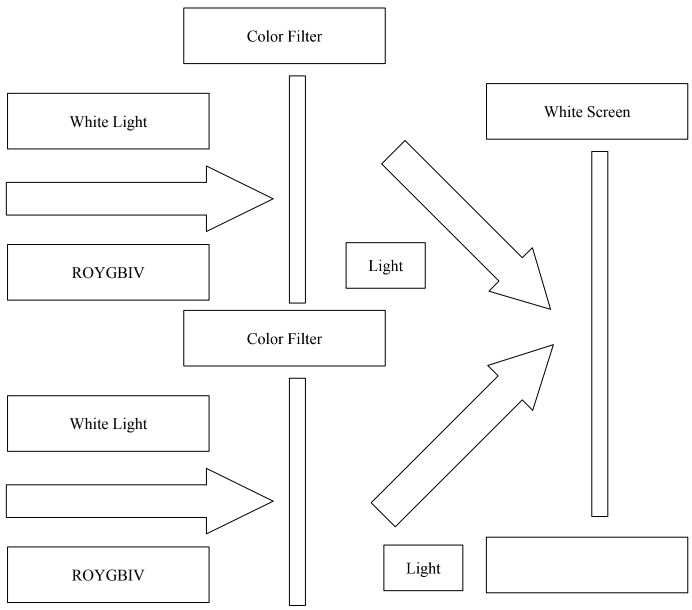
Handout 8:
Mixing Colored Lights and Filters

Follow the steps below for Explorations 1 and 2. Keep track of your results in the Color Mixing Data Table on the last page of this handout.

Exploration 1: Mixing Colored Lights

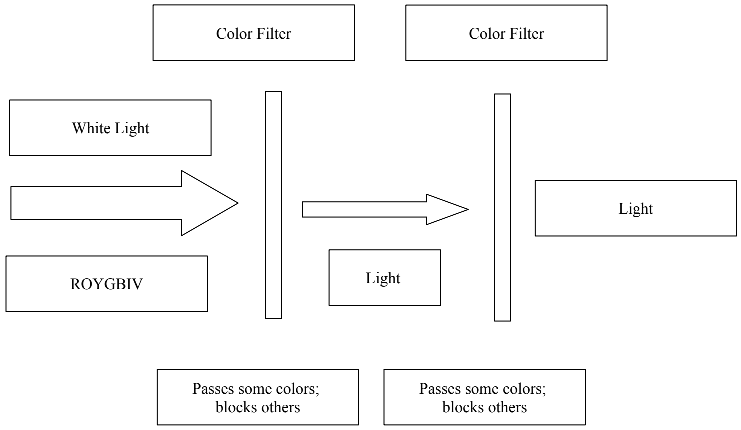


In the first exploration, you will create different-colored light sources and mix the colored light. This is the kind of color mixing that takes place in your eye and brain. As you conduct the experiment, keep in mind the colors of the "eye primaries."

Procedure

1. Using tape or rubber bands, attach one colored filter over each flashlight, so that you have one red, one green, one blue, and one yellow light.
2. Predict what color will result by mixing each given combination of colored lights in the Color Mixing Data Table. Record your predictions in the column labeled "Exploration 1: Mixing Colored Lights."
3. Project each light separately onto the wall or screen and observe its color.
4. Choose two of the colored lights—for example, red and green—and project them onto the wall so that their spots of light overlap. What color do you see where the spots overlap? Record your observation in the Color Mixing Data Table.
5. Repeat step 4 with each of the following pairs of colored lights: red + blue, blue + green, blue + yellow. Record your observations.
6. Project the three lights corresponding to the "eye primaries," so that their spots of light overlap. What color do you see where the spots overlap? Record your observation.

Exploration 2: Mixing Colored Filters



In this second exploration, you will use only one light source. You'll mix colored filters by placing one filter over another in front of the light source. Your results will be similar to those you would achieve by mixing paint. As you conduct the experiment, keep in mind the "traditional" primary colors ("paint primaries").

Procedure

1. Predict what color will result by mixing the combinations of colored filters shown in the Color Mixing Data Table. Record your predictions in the column labeled "Exploration 2: Mixing Colored Filters."
2. Use the flashlights with colored filters on them from Exploration 1. Take the flashlight with the blue filter. Hold a red filter directly in front of it and shine the light through the filter. What color is projected onto the wall or screen? Record your observation in the Color Mixing Data Table.
3. Hold the green and then the yellow filters in front of the flashlight with the blue filter. Record the color that is projected for each.
4. Next, shine the red-filter flashlight through the yellow filter. Then shine the red-filter flashlight through the green filter. What color is projected for each? Record your observations.
5. Finally, shine the red-filter flashlight through both blue and yellow filters at the same time. What color is projected? Record your observation.
6. Look at the Color Mixing Data Table. Compare your results when mixing two or more colored lights (Exploration 1) to your results when shining a single light through two or more filters (Exploration 2). Were the colors you observed similar or different? Describe.

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Color Mixing Data Table

	Exploration 1: Mixing Colored Lights	Exploration 2: Mixing Colored Filters
Red & Blue		
Predicted Color		
Observed Color		
Blue & Green		
Predicted Color		
Observed Color		
Green & Red		
Predicted Color		
Observed Color		
Blue & Yellow		
Predicted Color		
Observed Color		
Red & Yellow (filters only)		
Predicted Color		
Observed Color		
Blue, Red, & Green (lights only)		
Predicted Color		
Observed Color		
Red, Blue, and Yellow (filters only)		
Predicted Color		
Observed Color		

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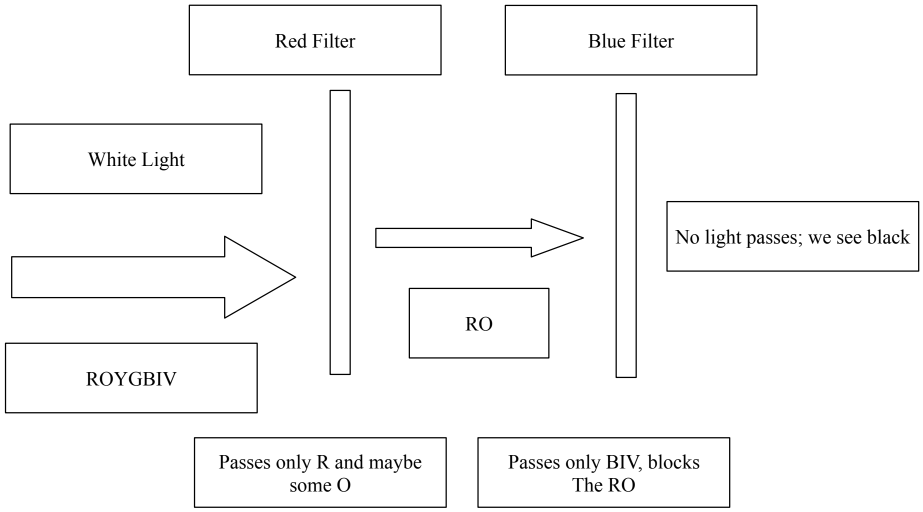
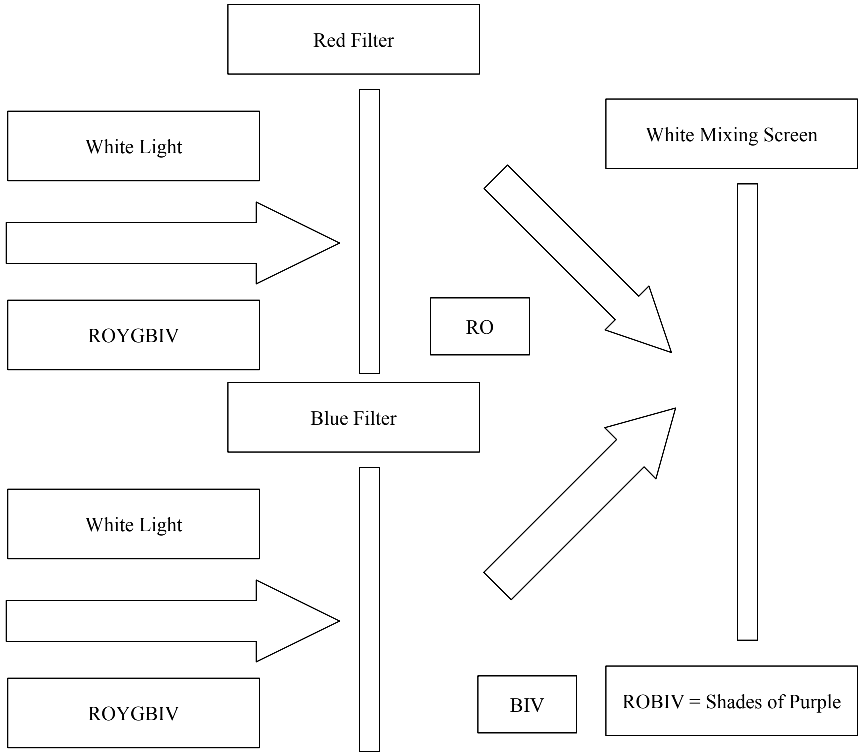
Handout 9:
Diagrams of Color Mixing



Subtractive Color Mixing: Each subsequent color filter blocks out, or absorbs, more wavelengths of light.

In the above example, the red filter absorbs the Blue, Indigo, and Violet wavelengths of light, passing through only Red and a small amount of Orange wavelengths. The blue filter then absorbs the Red and Orange wavelengths of light, so that the end result is no light, or black.

Each color filter absorbs or "subtracts" more colors from the original light source. In subtractive mixing, the resulting mixed color is always darker than any of the colors that it is composed of.



Additive Color Mixing: Each subsequent color adds more wavelengths of light.

In the example above, the red filter passes through the wavelengths of Red and Orange light and the blue filter passes through the wavelengths of Blue, Indigo, and Violet light. The net result is that the wavelengths are combined or "added" to make a purple shade.

In additive mixing, the resulting mixed color is always lighter than any of the colors that it is composed of.

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Handout 10:
Illusion 3: The Disappearing Dot

Procedure

1. Make a small dot on the left side of a plain white sheet of paper.
2. On the right side of the paper, about 6 inches away from the dot, draw a small +.
3. Close your right eye.
4. Hold the image about 20 inches away and look at the + with your left eye.
5. Slowly bring the image (or move your head) closer while looking at the +.
6. At a certain distance, something happens. What is it?
7. Now reverse the process. Close your left eye and look at the dot with your right eye.
8. Slowly move the image closer to you and observe what happens.

Based on your observations, formulate a question that you would like to have answered:

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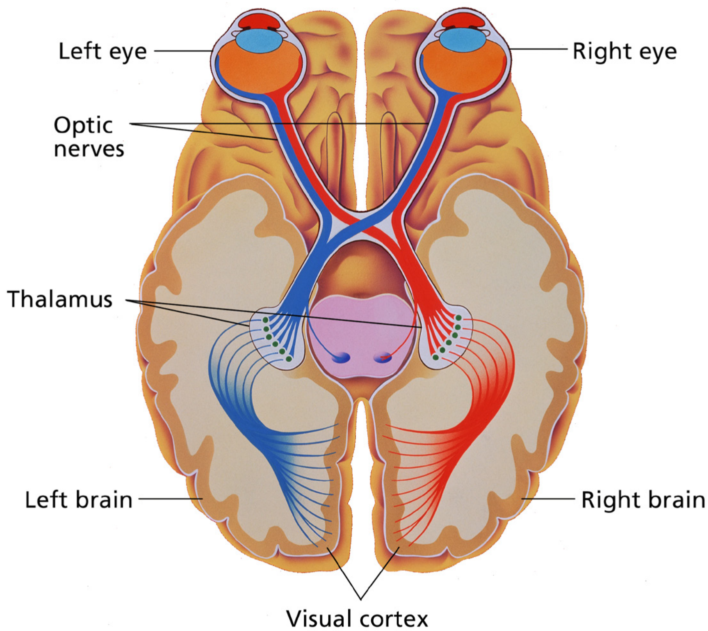
Handout 11:
Brain Connections

How Does the Brain Allow You to See?

The eye and brain function together in the nervous system to interpret visual stimuli. The optic nerve transmits the visual information via electrochemical impulses from the eye to the *thalamus*, the brain's upper relay center. The signals are then sent to the *visual cortex* in the brain's occipital lobe.



Vision and the brain
J. Bavosi / Photo Researchers, Inc.

The brain's visual cortex interprets the nerve signals. This is what allows you to see. Most of the time, the brain interprets these signals reliably—however, your brain is constantly making decisions about the information it receives based on your experience, memory, and immediate surroundings.

One of the most basic decisions the brain makes is to reorient the image it receives from the optic nerve. The image formed at the back of the retina and sent to the brain is inverted, but the brain corrects the image so that you see it right side up.

NAME DATE

What Is Your Blind Spot?

One way the brain interprets visual signals is to fill in missing information. There is one spot on your retina where all the nerve fibers gather together to form the optic nerve. This spot has no rods or cones—no photoreceptors at all. It is known as your *blind spot*.

Most of the time, you do not notice your blind spot. For example, when you look around you, or at a picture or a page of text, you don't see a blank spot in the middle of your field of vision. Why?

You don't see a blank spot because your eyes aren't the only organ of your nervous system involved in vision. Once sensory information exits the eye through the optic nerve, it travels to the brain, where the brain interprets the visual information.

Your brain compensates for your blind spot by filling in the blank area in the image, using the sensory image data from the surrounding region. So instead of seeing what's actually there, you see what *should* be there according to your brain's calculations. Most of the time this means you experience an accurate uninterrupted view of your surroundings. But sometimes . . . your brain makes a mistake.

Using what you have learned about your blind spot, can you come up with an explanation for Illusion 3?

NAME DATE

Handout 12:
The Equiluminance Effect

Explanation of the Equiluminance Effect

In the two paintings, you observed how the colors and figures seemed to move on their own. This can be explained by the way the brain processes visual signals.

Two systems in the brain's visual cortex are responsible for visual perception:

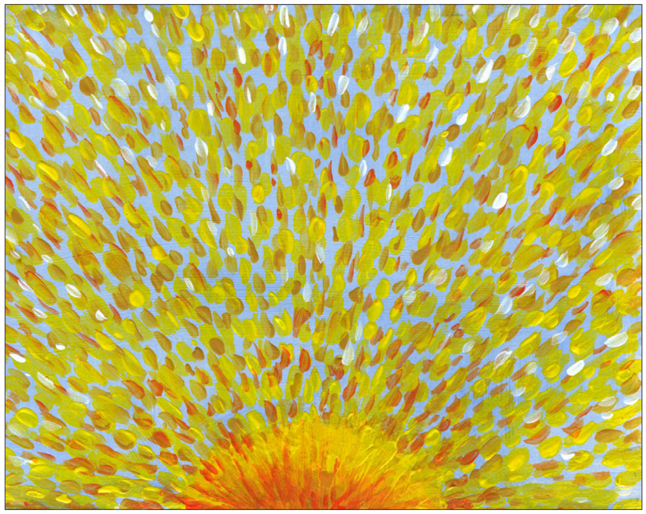
- The "Where" system—which controls our perception of motion, space, position, depth, figure/ground separation, and organization
- The "What" system—which helps us recognize objects, including faces, in color and detail

Normally, the brain's "Where" system uses differences in color luminance to distinguish an object from its background. However, when two colors, or the colors of two adjacent figures, are equiluminant—i.e., have the same brightness—the "Where" system cannot distinguish where one color ends and the other begins.

The result is that the "What" system sees the colors and shapes of the figures, but the "Where" system cannot locate them spatially. This creates an effect where colors and shapes seem to vibrate or float and do not remain still.

NAME DATE

Handout 13:
Pointillism



Drops of light in pointillistic technique.
Photograph from iStockphoto.

Look closely at the painting above. Describe what you see.

Can you guess what the painting style pointillism refers to?

Pointillism became popular in Europe in the late 1900s. One of the most famous pointillist painters was Georges Seurat. His painting *Sunday Afternoon on the Island of Grande Jatte* was the first publicly displayed and recognized pointillist painting.

Pointillist painters were very interested in the effects of light, and many were aware of scientific theories about color perception. In pointillism, as with most painting techniques, artists begin by using subtractive mixing to develop a basic color palette. But unlike other painting styles, the pointillist artist paints with a limited number of pre-mixed colors. The wider range of colors perceived in the painting are created with a third type of mixing, partitive mixing, which occurs as an active component of viewing the painting.

When you view this painting, how do you think color mixing is taking place?