Chapter 6

**COLOR PERCEPTION**

Humans can see wavelengths of light within the visual spectrum (between 400 and 700nm). Different wavelengths are seen as different colors, but other properties also control color perception. Color perception is often discussed in terms of three dimensions. First, hue refers to the color quality of the light and corresponds to the color names we typically use. Second, saturation refers to the purity of light. Third, brightness refers to the amount of light present. Colors can be mixed in two ways: additive color mixing and subtractive color mixing. Additive color mixing is the creation of a new color by a process that adds one set of wavelengths to another set of wavelengths, as when lights are mixed. Subtractive color mixing is the creation of a new color by the removal of wavelengths from a light with a broad spectrum of wavelengths, as when paints are mixed. Color vision begins with the S-cones, M-cones, and L-cones in the retina, which each have a maximum response to different wavelengths. The existence of these three cones supports the trichromatic theory of color vision, which states that the color of any light is determined by the output of the three cone systems in our retinae. Conversely, color afterimages and hue cancellation studies support the opponent theory of color vision, which states that color perception arises from three opponent mechanisms, for red-green, blue-yellow, and black-white. Cone-opponent cells are located in the LGN and V1.The visual system is also adept at the ability to perceive the color and relative reflectance of objects despite different conditions.

Usually the result of genetic defects and more common in men, color deficiency refers to the condition of individuals who are missing one or more of their cone systems. In rod monochromacy, no functioning cones of any kind are present, resulting in true colorblindness. In cone monochromacy, only one type of cone is present. In dichromacy, two working cone systems are present. The major forms of dichromacy are protanopia (lack of L-cones, red-green deficiency), deuteranopia (lack of M-cones, red-green deficiency), and tritanopia (lack of S-cones, blue-yellow deficiency). Anomalous trichromacy occurs when all three cone systems are present but the absorption pattern is altered. In unilateral dichromacy, only one eye is affected by dichromacy but the other eye has normal trichromatic vision. Finally, in cortical achromatopsia, loss of color vision occurs because of damage to the occipital lobe.

Introduction

* Colors are usually properties of objects.
* Cats and dogs are color deficient, meaning that they have a two cone system instead of the human three cone system.
* Goldfish have a four cone system, and research suggests they can see color differences that appear the same to most humans.
* However, a rare few humans have a four cone system and seemingly see more colors than those with a three cone system.
* Genetically speaking, men are more likely to be color deficient (two cone system) and less likely to have the extra cone system.

Wavelengths of Light and Color

* Humans can see wavelengths of light within the **visual spectrum** (between 400nm and 700nm).
  + Different wavelengths are seen as different colors.
  + The physical stimulus is the wavelength of light entering the eye; color is a perceptual attribute.
  + In color vision, wavelength of light is usually referred to, whereas frequency is usually used for sound waves.
* Blending several wavelengths together, sunlight forms white light.
  + The wavelengths are bunched together, so we cannot differentiate them in white light.
  + However, because sunlight is made up of so many wavelengths, raindrops can diffract (i.e., spread out) the light into the multiple wavelengths that make up a rainbow.
  + Natural sunlight varies in the distribution of wavelengths throughout the day.
    - At noon, there is more blue light; at evening, there is more red light.
* Artificial light sources tend to be mixes of wavelengths and can thus be classified as white light.
* **Heterochromatic light** consists of many wavelengths (white lights), whereas **monochromatic light** is light of only one wavelength or a narrow band of wavelengths.
  + When monochromatic light reflects off a white surface, that surface is seen as the color associated with that wavelength.
* **Spectral reflectance**, another important feature in color perception, is the ratio of light reflected by an object at each wavelength.
  + That is, every object has particular characteristics that allow it to absorb some wavelengths of light and reflect others.
  + The color of any object is determined by the wavelengths it reflects the most.
  + For example, bananas are yellow because they absorb most wavelengths but reflect yellow light.
* Surfaces that reflect all light equally are achromatic (without color).
  + These surfaces are said to be white to gray to black. What matters is the proportion of ambient light they reflect.
  + An important property of the visual system is that we respond to the proportion reflected rather than the total amount reflected.

Hue, Saturation, Lightness, and Brightness

* Color perception is often discussed in terms of three dimensions: hue, saturation, brightness.
* **Hue** refers to the color quality of the light and corresponds to the color names that we use.
  + Hue is a **quality**, meaning it is a value that changes but the change does not make the value larger or smaller.
  + Colors associated with particular wavelengths are called monochromatic colors, which include basic or spectral colors (i.e., red, green, orange, yellow, blue).
  + Colors made of combinations of more than one monochromatic colors are known as nonspectral (e.g., purple, brown, silver, gold).
* **Saturation** refers to the purity of light.
  + The more saturated the stimulus, the stronger the color experience. The less saturated the stimulus, the more it appears achromatic.
  + The classic example of saturation differences is the continuum from red to pink. Pink is a combination of red and white light. The more white light added, the less “red” the pink is.
* **Brightness** refers to the amount of light present.
  + The brighter an object is, the easier it is to see and the more evident its colors are.
  + Brightness is distinguished from **lightness**, which refers to the amount of light that gets reflected by a surface.
* Hue and saturation can be represented in a color circle, a two-dimensional representation of how hue and saturation interact.
* Hue, saturation, and brightness can be represented in a color solid, a three-dimensional representation of how hue, saturation, and brightness interact.

Additive and Subtractive Color Mixing

* Most sensations and perceptions do not mix in the ways colors do.
* There are two main types of color mixing: additive color mixing and subtractive color mixing.
* **Additive color mixing** is the creation of a new color by a process that adds one set of wavelengths to another set of wavelengths.
  + This occurs when we mix lights.
* **Subtractive color mixing** is the creation of a new color by the removal of wavelengths from a light with a broad spectrum of wavelengths.
  + This occurs when we mix paints.

Additive Color Mixing (Mixing Lights)

* On a television or computer screen, what one sees is a mix of three different light sources controlled at different intensities.
* The color circle can be used to predict perceived colors in additive mixtures.
* In the late 19th century, artists such as Georges Seurat and Vincent van Gogh invented a painting technique that came to be known as pointillism.
  + An artist uses small distinct dots of simple primary colors as the basis of a painting. From a distance, the dots of colors blend together through a process similar to additive color mixing, which is unique in painting because most techniques use subtractive color mixing.

Subtractive Color Mixing (Mixing Paints)

* Subtractive color mixing is more common in the natural world.
* It occurs when we mix substances with different absorption spectra.
* That is, when we mix substances, the mixtures absorb the wavelengths both substances absorb, leaving only those wavelengths to reflect what both do not observe.

Color-Matching Experiments

* Many psychophysical experiments have examined the perceptual reality of color matching and are known as metameric color-matching experiments.
* A **metamer** is a psychophysical color match between two patches of light that have different sets of wavelengths.
  + That is, a metamer consists of two patches of light that look identical in color but are made up of different physical combinations of wavelengths.
* In a metameric color-matching experiment, a participant is shown two patches of light, a test patch (a single wavelength of an unchanging brightness) and a comparison patch (composed of three primary colors).
  + The participant has the task of adjusting the levels of each of the three primary colors so that the color of the comparison patch matches the color of the test patch.
  + It should be noted that the colors are combined with additive color mixing.

The Retina and Color

* There are three classes of cones in the foveae of the retinae.
* Each cone type contains a different photopigment and is thus sensitive to a different band of wavelengths.
* The **S-cone** has a maximum response to light at 420nm (short wavelength).
* The **M-cone** has a maximum response to light at 535nm (medium wavelength).
* The **L-cone** has a maximum response to light at 565nm (long wavelength).
* When these three cone systems are combined, we can see color over a range of approximately 400 to 700nm.
* There are many more M- and L-cones than there are S-cones. S-cones only make up 5% of the cones.
* S-cones are less sensitive than M- and L-cones, meaning they are less important in brightness perception but are still important in color perception.
* When reflected light hits the retina, there will be a pattern of responses in the three cone systems that induce the experience of a particular color.

Univariance, or Why More Than One Receptor Is Necessary to See in Color

* **Univariance** is the principle whereby any single cone system is colorblind, in the sense that different combinations of wavelength and intensity can result in the same response from the cone system.
* That is, color vision requires the comparative inputs of the different cone systems.
* No individual cone system can, by itself, distinguish colors.
* Univariance also explains why colors are not seen at night.
  + When under scotopic conditions (dim light), only the rod system is used.
  + Because there is only one class of rods, no color is seen under these conditions.

The Trichromatic Theory of Color Vision

* The first modern theory of color vision was proposed by Thomas Young in the 19th century and further developed by Hermann von Helmholtz.
  + They advanced a theory similar to what is now known as the trichromatic theory.
* The **trichromatic theory of color vision** states that the color of any light is determined by the output of the three cone systems in our retinae.
* Evidence supporting the trichromatic theory:
  + Color-matching experiments show that it takes a minimum of three primary colors to make a metameric match to a single monochromatic light.
  + There is overwhelming evidence of the existence of three classes of cones in the human retinae.
  + The trichromatic theory predicts what happens when a person loses a cone class.
    - The person still sees in color, but cannot distinguish between hues normal three-coned individuals can.
    - In the classic form, most color-deficient people cannot distinguish between reds and greens due to the loss of either M- or L-cones.

The Opponent Theory of Color Perception

* The opponent theory of color perception is the traditional rival theory to the trichromatic theory.
* We now know that each theory explains certain aspects of color perception that the other theory cannot explain.
* The **opponent theory of color perception** states that color perception arises from three opponent mechanisms, for red-green, blue-yellow, and black-white.

Findings That Support Opponent Theory

* Ewald Hering proposed that color vision was organized with four primaries, or unique hues.
* Following are important reasons that the opponent theory was advanced:
  + Nonprimary colors can look like combinations of two primary colors.
    - Our perception of colors supports the idea that red and green do not combine and that blue and yellow do not combine.
  + In color-sorting experiments, people tend to sort colors into four basic groups (red, green, yellow, and blue) rather than three colors.
  + Color **afterimages** are visual images seen after an actual visual stimulus has been removed.
  + **Simultaneous color contrast** occurs when perception of one color is affected by a color that surrounds it.
    - This effect occurs when a color is surrounded by its opponent color and not by other colors or achromatic backgrounds.

Hue Cancellation

* Hurvich and Jameson (1957) conducted a series of important experiments describing **hue cancellation**, which supports the opponent theory.
  + Participants saw a monochromatic light at a wavelength between two particular primary colors.
  + Then, the participant was given control over the amount of a second light that could be added to the first, through additive color mixing with the instructions to cancel out the blue so that the light appeared only as green.
  + The results showed that only yellow light could cancel out the blue light (and vice versa).
* Some colors can be described in terms of other colors (e.g., orange is a mix of yellow and red) whereas **unique colors** can only be described in terms of themselves (red, green, blue, yellow).

Opponent Cells in the LGN and V1

* Opponent cells in the LGN and V1 respond in a center-surround fashion.
* In the LGN, **cone-opponent cells** respond best when they are excited by the input from one cone in the center, but inhibited by the input from another cone type in the surround.
* In V1, **color-opponent cells** respond to one color in the center and are inhibited by its opponent color in the surround, or vice versa.
* In V1, **double-opponent cells** have a center, which is excited by one color and inhibited by the opponent, but in the surround the pattern is reversed.
  + These cells are useful for detecting color edges.

Color Deficiency

* **Color deficiency** refers to the condition of individuals who are missing one or more of their cone systems.
* Color deficiencies are usually the result of genetic defects and are more common in men because the genes leading to color deficiency are on the X chromosome.
* Color deficiency is most often determined using Ishihara plates, in which different colored, but isoluminant dots are presented.

Rod Monochromacy

* Rod monochromacy is a very rare form of color deficiency, affecting 1 in every 30,000 people.
* No functioning cones of any kind are present, resulting in true colorblindness.
* Individuals with rod monochromacy:
  + See the world in shades of gray.
  + Are very sensitive to bright light because they always use scotopic vision.
  + Have very poor visual acuity.

Cone Monochromacy

* Cone monochromacy is an extremely rare form of color deficiency, affecting 1 in every 100,000 people.
* Only one functioning cone system is present.
* S-cone monochromats have been observed—they have S-cones but lack M- and L-cones.
  + Given the low overall sensitivity of S-cones, S-cone monochromats have similar symptoms of rod monochromats, but they are less severe.

Dichromacy

* Dichromats have two working cone systems.
* They see in color, but cannot make some of the discriminations that are easy for trichromats.
* There are three major forms of dichromacy: protanopia, deuteranopia, and tritanopia.
  + **Protanopia** is a lack of L-cones due to a deficient gene, leading to red-green deficiency.
  + **Deuteranopia** is a lack of M-cones due to a deficient gene, leading to red-green deficiency. The difference between deuteranopia and protanopia is where the wavelengths that can be seen cross over.
  + **Tritanopia** is a lack of S-cones, leading to blue-yellow color deficiency. It is not sex-linked
* There is also a form of color deficiency called **anomalous trichromacy** in which all three cone systems are present but one or more has an altered absorption pattern, leading to different metameric matches than in normal people.
* A very few people have **unilateral dichromacy,** in which there is dichromacy in one eye but normal trichromatic vision in the other eye.
  + Unilateral dichromacy allows researchers to understand the true nature of dichromacy.

Cortical Achromatopsia

* In **cortical achromatopsia,** loss of color vision occurs because of damage to the occipital lobe, usually from damage to V4.
* The primary symptom is seeing in black, white, and gray or having the impression that colors are washed out.
* Sometimes, patients can still discriminate by wavelength.
* In other cases, patients lose the ability to remember color.

Constancy: Lightness and Color Constancy

* **Constancy** refers to the ability to perceive an object as the same object under different conditions.

Color Constancy

* **Color constancy** refers to the ability to perceive the color of an object despite changes in illumination.
* A system that sees an object as a constant color across such changes leads to accurate perception.
* Color constancy is probably achieved by an implicit comparison across different objects in a scene, which each reflect different wavelengths, allowing the visual system to extract the illumination from known reflective properties.
* There are several situations in which color constancy fails.
  + Monochromatic light allows an object to only reflect that wavelength and appear the color of that light.
  + When an object is viewed in front of a pure black background, it makes it difficult for the visual system to get the context to see the object as the right color.

Lightness Constancy

* **Lightness constancy** refers to the ability to perceive the relative reflectance of objects despite changes in illumination.
* The easiest way to think of lightness constancy is to think of it along the continuum from black to gray to white.
* The **Gelb effect** is an exception to lightness constancy in which an intensely lit black object appears to be gray or white in a homogenously dark space.

***In Depth: The Color Purple***

* In practice, purple and violet are very similar perceptually, but technically, they refer to different kinds of color.
* Violet is a spectral color seen at the very shortest wavelengths of the visual spectrum.
* Purple is a nonspectral color that cannot be generated by a single wavelength of light. It is a mix of red light and blue light.