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What is color and how it is perceived?

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Abstract The physical nature of color is well known and is based on its wavelength; however, the color perception in humans and animals is much less understood and is based mostly only on some assumptions and theories. We present the current knowledge on both of these topics, describe the anatomic basis for color vision, and discuss color vision deficiencies. Color vision disturbances can not only interfere with everyday activities but also impede performing specific professions. Commercial or military pilots, electricians, defense forces including paramilitary, food and art critics, and some physicians, scientists, and engineers may not be able to perform their professions to the full extent. Colors play an important role in the culture of various societies. The same color can have the opposite meaning in different cultures. Lack of knowledge of these meanings, when overcoming huge distances, is no longer a problem, but it can lead to unpleasant misunderstandings. Such cultural meanings of color are also discussed.
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Colors

The human eye can detect visible light, which is a small part of the electromagnetic spectrum that includes radio waves, microwaves, infrared radiation, visible light, ultraviolet light, X rays, and gamma rays (Figure 1). Visible light waves consist of various wavelengths that are perceived as assorted colors (Figure 2) The color we see is a result of those wavelengths that are reflected to our eyes (Figure 3). These wavelengths range from 700 nm at the red end of the spectrum to 400 nm at the violet with a peak sensitivity at 555 nanometers in the green region of the visible light spectrum; however, it is not usual to see light of a single wavelength.

There are currently three known types of photoreceptor cells in mammalian eyes:

- rods
- cones
- photosensitive retinal ganglion cells (Figure 4)

These rods enable perception in black, white, and gray. The cones are responsible for detecting colors. Cones only work when the light is bright enough but are diminished when light is dimmed. At very low lighting levels (less than 0.035 cd/m^2), cones do not function. They begin to contribute to visual perception at about the level of starlight.[1] The maximum sensitivity of the rods lies in the visible light wave with a length of approximately 500 nm and almost three times lower intensity of light to which cones react. In the grouping of cones, three types of photoreceptors are sensitive to different wavelengths of light, which are interpreted by the brain as red, green, and blue.

L-type cones (long) react most intensively to a visible wavelength of approximately 560 nm. They are sensitive to the longest electromagnetic wave in the visible light range.

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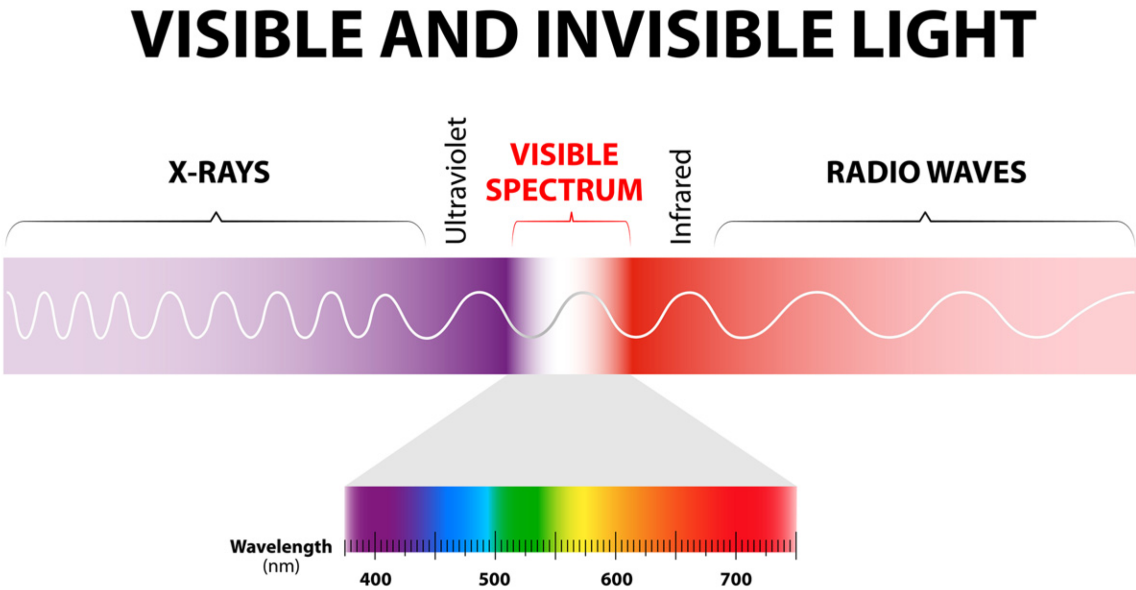

Fig. 1 The spectrum of waves. Source: Downloaded from Shutterstock.com. Standard publishing license.

At an electromagnetic wave with a length of approximately 530 nm, cones are marked type M (middle), because their maximum sensitivity falls on a visible light wave with an intermediate length between long and short.

- Blue light has a length of approximately 420 nm; cones type S (short) react most intensively because their maximum sensitivity is associated with the shortest wavelengths of visible light.
- Red items looks red because the dye molecules in red fabric has absorbed the wavelengths of light from the violet/blue end of the spectrum, making red light the only light that is reflected from the material.
- White light is composed of all of the colors of the rainbow, as it contains all wavelengths, making it polychromatic light.
- Black objects absorb all colors with no light being reflected.

Birds have four types of cones; therefore, except for owls and other nocturnal ones, they can see ultraviolet. Insects also have a similar capacity. In practice, this allows a doubling of the available color palette. As a result, white color will have different shades for each animal that differ significantly. Some birds have beautiful patterns on the plumage seen only in the ultraviolet. In addition, such vision allows raptor birds to see from their flight much more readily than do humans. It helps them, for example, in search for food.

Birds and reptiles have infrared vision. This is the reason hunters wear bright orange jackets that are recognized by forest animals as gray but not by foxes and wolves.[2] The Australian beetle (*Merimna atrata*) has exceptional visual abilities due to very sensitive infrared receptors and is able to "see" fire from many kilometers away.[3]

In 1923, Clyde E. Keeler (1900-1994) suggested the existence of ganglion cell photoreceptors when he observed that rodless, coneless mice still responded to a light stimulus through pupil constriction. This suggested that they are not the only light sensitive neurons in the retina.

More advanced research began in the early 1980s.[4] Intrinsically photosensitive retinal ganglion cells, also called photosensitive retinal ganglion cells or melanopsin-containing retinal ganglion cells, are a type of neuron in the retina. They

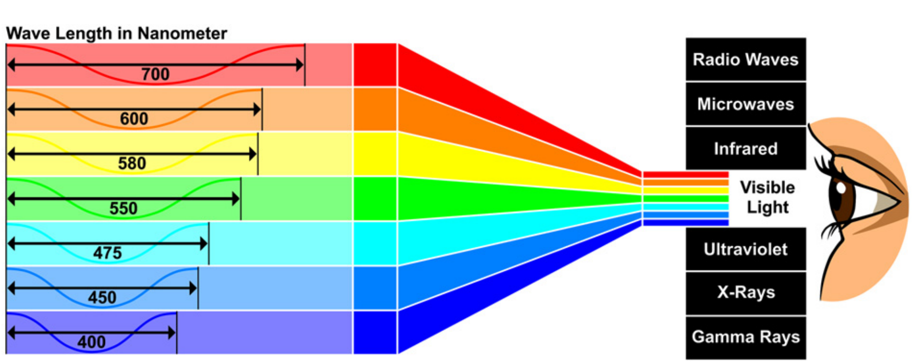

Fig. 2 Visible light with wavelength difference between spectra colors. Source: Downloaded from Shutterstock.com. Standard publishing license.

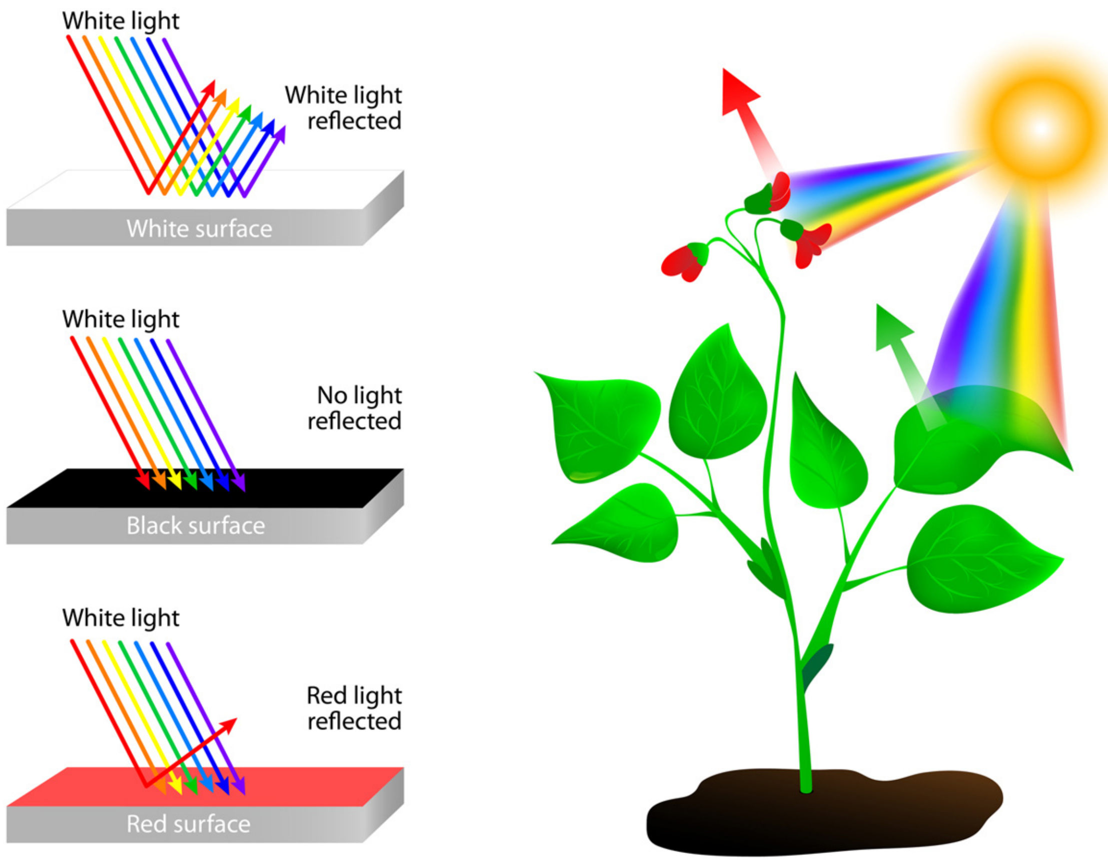

Fig. 3 Reflection and absorption of the different colors in white light. Source: Downloaded from Shutterstock.com. Standard publishing license.

have the unique ability to communicate directly with higher visual centers of the brain. These intrinsically photosensitive retinal ganglion cells are a rare subpopulation of ganglion cells (<5%).[5] They do not create an image but provide information on the ambient light intensity. They have at least three basic functions:

- provide information about the length of day and night, thereby synchronizing the circadian rhythm with a 24-hour light/dark cycle
- innervate centers, such as the pupil control center, contributing to the pupil size adjustment depending on the ambient lighting conditions
- regulate the level of melatonin hormone release[6]

The colors red, green, and blue are classically considered the primary colors, because they are fundamental to human vision. Mixing these colors in different proportions provides all the colors that we see (Figure 5). Despite intense studies and modeling, human stereo color vision is a very complex process that remains incompletely understood.

The human eye is equipped with a variety of optical components including the cornea, iris, pupil, aqueous and vitreous humors, a variable-focus lens, and the retina. Vision involves the brain through a network of neurons, receptors, and other specialized cells. The first step in this sensory process are the stimulation of light receptors in the eyes, conversion of the light stimuli or images into signals, and transmission of electrical signals containing the vision information from each eye to the brain through the optic nerves. The visual cortices of the cerebrum process this information in the end.

Present concepts of creating a color image in the brain

Trichromatic color theory

The trichromatic theory explains how color vision works at the receptor level. The theory assumes that color vision results from the actions of three different receptors. Thomas Young (1773-1829) in 1807 put forward the trichromatic theory of vision in a recognizable form.[7] Adopting a wave theory of light, he grasped that the physical variable was a wavelength and was continuous, whereas the trichromacy of color matching was imposed by the physiology of our visual system. He presented the concept that the retina is not made of nerve fibers filled with three pigmentary molecules

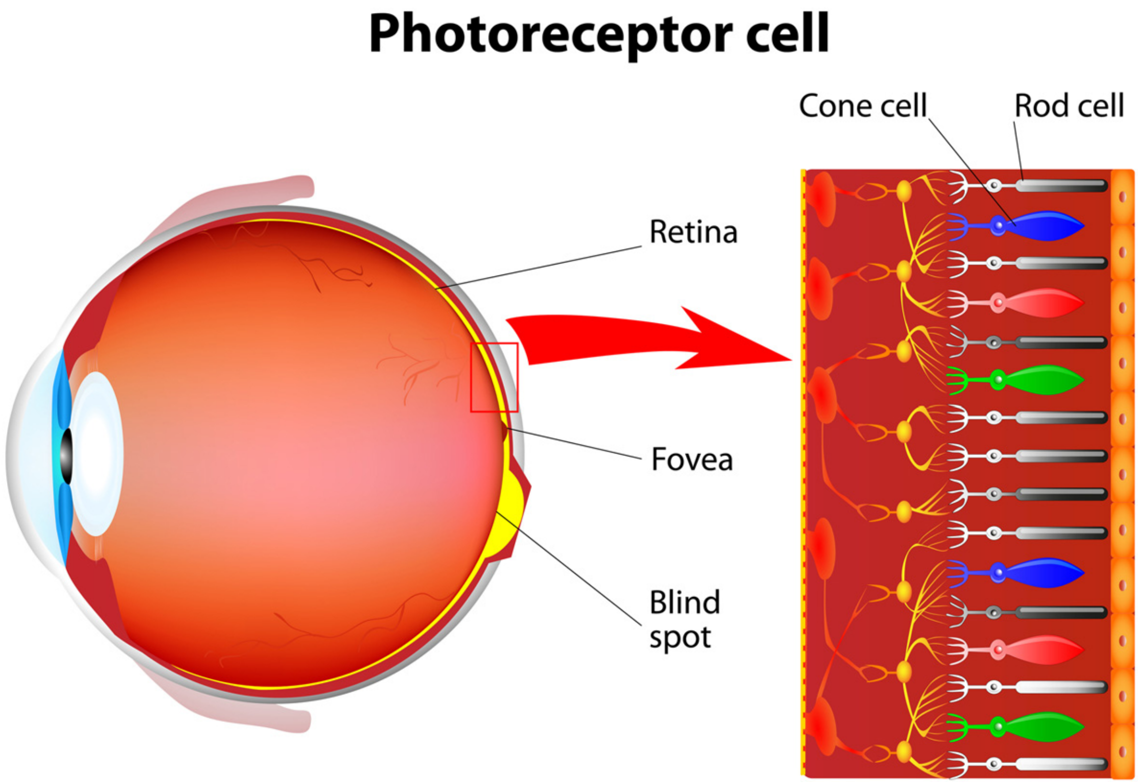

Fig. 4 Photoreceptor cells in the retina of the eye. Structure and function rod cells and cone cells. Source: Downloaded from Shutterstock.com. Standard publishing license.

but of three types of receptor cells that react with different intensity to light rays covering the entire range of visible light. Young suggested ignoring the idea of mixing colors in the eye. In return, Young postulated the concept of adding up

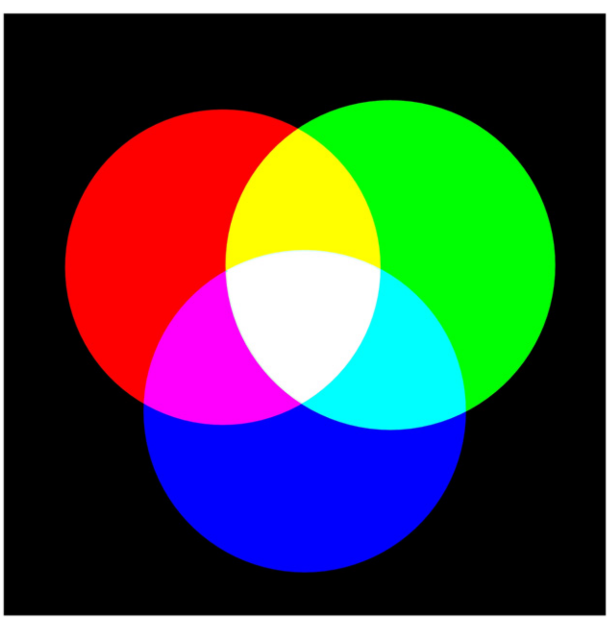

Fig. 5 Mixing colors (RGB). Source: Downloaded from Shutterstock.com. Standard publishing license.

the reaction force of receptors to stimulating a wave of light of various lengths, although he generally agreed with the idea that all colors are a derivative of the mixing of the three components. As the basis for such determination, he adopted a spectrum of colors obtained as a result of the dispersion of white light. He arbitrarily concluded that three points of maximum receptor sensitivity are associated with blue, green, and red. After the division of the entire spectrum of visible light into these three parts, the colors distinguished dominate within each category.[8]

Relationships between the length of the light wave and the sensitivity of Young's three types of photoreceptors was developed by the German physiologist and physicist Hermann von Helmholtz (1821-1894) in 1851.[9] Similar to Young, he believed that seeing different colors is associated with the diverse sensitivity of photoreceptors to all wavelengths of visible light. He also considered that each type of photoreceptor has a specific wavelength of light for which that particular photoreceptor is the most sensitive.

Helmholtz is largely responsible for establishing the trichromatic theory. He had previously invented the ophthalmoscope and measured the velocity of nerve conduction.[9] His first contribution explains the difference between additive and subtractive color mixture by considering absorption at an object's surface in terms of layers of thin filters. He showed that most wavelengths had complementary colors, except for a region in the green part of the spectrum for which purple is the complementary hue.[9]

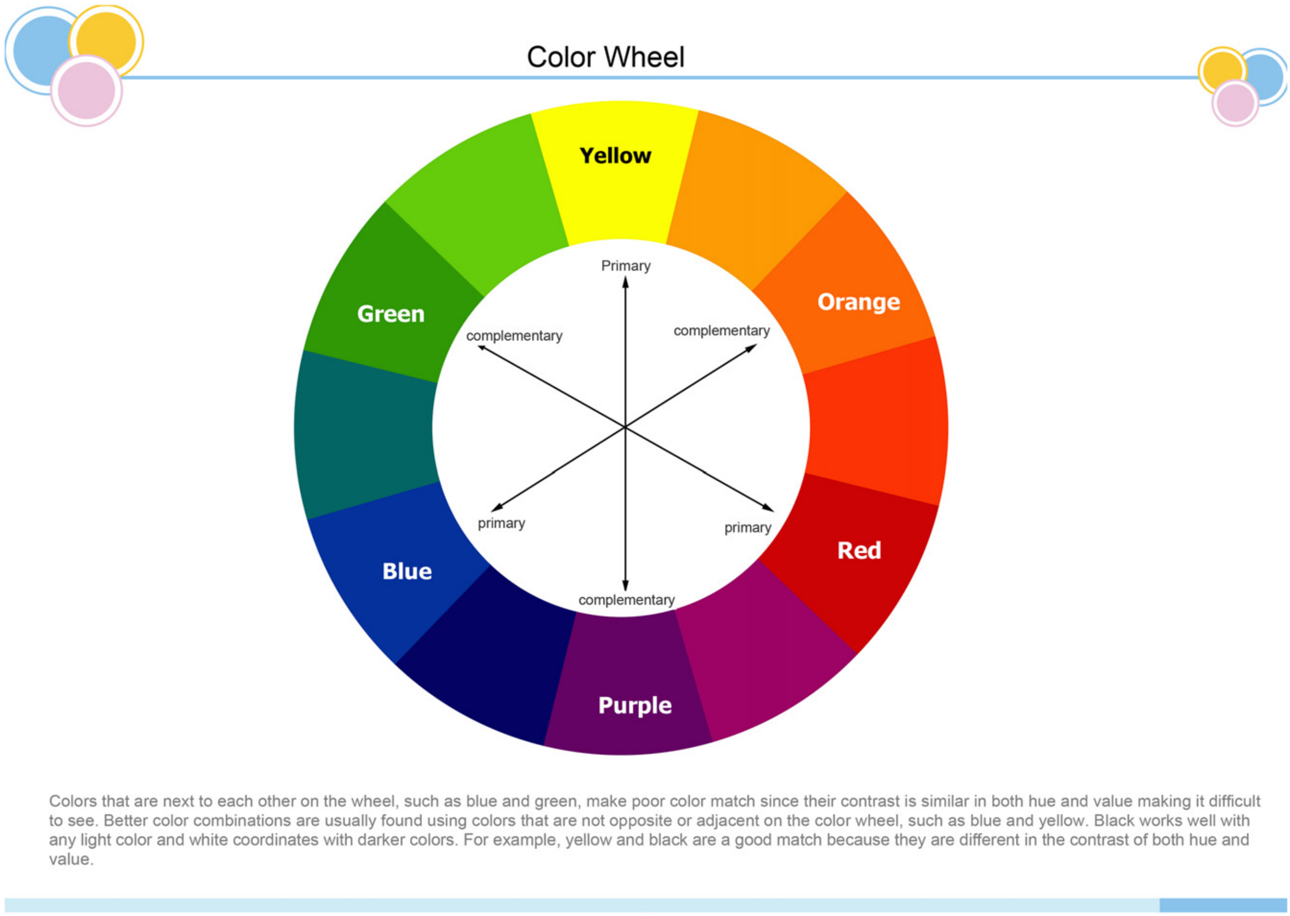

Fig. 6 Color wheel. Complementary colors. Source: Downloaded from edrawsoft.com. Free license.

Complementary colors are pairs of colors that create white light when combined[7] (Figure 6). As late as 1956 Gunnar Svaetichin (1915-1981) empirically confirmed he concept of three types of light-sensitive receptors of different length developed by Young and Helmholtz.[10,11] He showed that the retina has three types of photoreceptors, which are

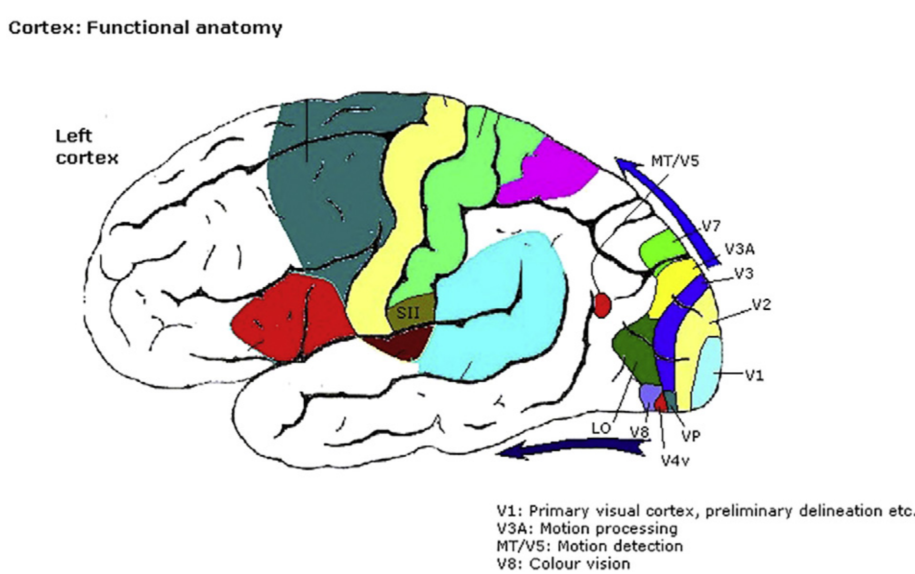

Fig. 7 Cortex. Source: Downloaded from the Wikimedia Commons. This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license.

particularly sensitive to three different wavelengths, corresponding somewhat to the blue, green, and red colors that had been postulated by Young and Helmholtz. A few years, later similar results were obtained by biophysicists from Johns Hopkins University[12] during studies on photoreceptors found in the retina in the eyes of monkeys. At the same time, biologists from Harvard University[13] observed photoreceptors located in the retina of the human eye.

Neither Young nor Helmholtz suspected that there might be two kinds of photoreceptors in the eye, one of which is sensitive to intense daylight and the other is active for night conditions. Basically, their concept involved only the first type of receptors—cones.

Opponent process theory

Opponent process theory is an alternative concept created in 1878 by Ewald Hering (1834-1918) in relation to the trichromatic theory of the seeing colors of Young and Helmholtz. As the basis for his theory, Hering also used the results of Newton's research on the cleavage of white light into many-colored components; however, he rejected the hypothesis of a triad of receptors sensitive to red, green, and blue, arguing that this idea does not explain the subjective impression of a yellow color being as pure and primitive as red, green, and blue. Hering noted that as a result of mixing certain colors in different proportions, new shades form that constitute a tonal transition between them, but mixing others does not produce such effects. Hering concluded that there are cells in the retina that create pairs responsible for the perception of opposing colors, red plus green and blue plus yellow, that mix with each other to create new quality, not intermediate forms.[9] Support for Hering's concept of oppositional colors is the experience of a colored after-image, also called postcontrast. This is a type of visual illusion that arises from long-term stimulation of different parts of the retina with different colors.[11]

Zone theory

The Young-Helmholtz's trichromatic theory and Hering's theory of opposing processes were treated as two contradictory concepts explaining the mechanism of seeing colors. The solution to this theoretical impasse was proposed by George Elias Müller (1850-1934),[14] when he presented the concept of color-coding zones on the visual path—zone theory. Müller suggested the following:

- The first zone is associated with the reactivity of red, green, and blue retinal photoreceptor responsive light.
- The second zone is the visual pathway on the retina segment—the cerebral cortex.
- The third zone is associated with the activity of cortical structures.

The first zone, including structures inside the retina of the eye, and also L, M, and S type receptors, was partly described by Young and Helmholtz as part of the trichromatic theory of color vision. The second zone is associated with the structure of connections and the activity of ganglion cells, which lead the signal from the retina of the eye to the lateral body and further to the cortical structures of the brain. The data from the photoreceptors are organized in this section exactly as Hering described it in his theory of opposing processes. Finally, the third color-coding zone covers the cortical areas of the brain, starting from the speckle areas in V1 (striate cortex) and ending with the V4 structure in the temporal lobes[8,9,14,15] (Figure 7).

Color vision deficiency

Color vision deficiency is usually inherited, but rarely it can be acquired. It is most commonly inherited from mutations on the X chromosome, where the M and L opsin genes are found. That is why men are more likely to be color blind than women. The most common form is red-green color blindness (protanopia), followed by difficulty distinguishing between blue and yellow (tritanopia), and finally total color blindness (achromatopia). Red-green color blindness affects up to 8% of men and 0.5% of women.

The ability to see color also decreases in old age. Factors that can contribute to changes in color vision with age and in particular blue-yellow vision are reduced pupil size and thus less light into the eye, changes in the sensitivity of the vision pathways, and increased opacity of the lens inside

Table 1 Types of red-green color blindness

Protanopia	1% of men	Lack of red cones	Problems in distinguishing between colors in the green-yellow-red section of the spectrum
Deuteranopia	1% of men	Lack or malfunction of the green cones	Problems in distinguishing between colors in the green-yellow-red section of the spectrum
Protanomaly	1% of men, 0.01% of women	Mutated form of the long-wavelength pigment (red)	Less sensitive to red light than normal
Deuteranomaly	6% of men, 0.4% of women	Mutated form of the medium-wavelength pigment (green)	Less sensitive to green light than normal

Table 2 Types of blue-yellow color blindness

Tritanopia	Less than 1% of men and women, not sex-linked	S-cones missing, long- and medium-wavelength cones are present	Decreased recognition of blue and yellow
Tritanomaly	0.01% of men and women, rarest form of anomalous trichromacy color blindness	Mutated form of the short-wavelength (blue) pigment	Short-wavelength pigment is shifted toward the green area of the spectrum

Table 3 Causes of color blindness

Causes of color blindness		
Diseases	Drugs	Chemicals
Diabetes, hypertension, multiple sclerosis, Parkinson disease, sickle cell anemia, AIDS, syphilis, diabetes insipidus	Streptomycin, ethambutol, rifampicin, isoniazid, sulfonamides, atropine, chloramphenicol, quinine	Ethanol, nicotine, heroin, methyl alcohol, benzene, styrene, carbon monoxide, lead

the eye associated with cataract formation.[16] The different kinds of inherited color blindness result from partial or complete loss of function of one or more of the three different cone systems. When one cone system is compromised, dichromic vision results.[11] Different types of red-green color blindness are presented in Table 1 and of blue-yellow color blindness in Table 2.

Total color blindness (monochromic vision) is defined as the inability to see any color. It is a rare disease, characterized by a reduced number or absence of cone functions. Patients with achromatopsia have significantly reduced visual acuity of about 20/200, nystagmus, and photophobia. Autosomal recessive mutations affect the genes of the cone phototransduction cascade. Some patients have unidentified causal mutations. Patients usually show complete loss of cone functions, as demonstrated by electroretinography studies. Achromatopsia affects all three classes of photoreceptors, and thus it refers to the genes that are expressed in all subtypes of suppositories.[17]

Acquired color blindness can be classified as caused by the following:

- diseases
- drugs
- chemicals (Table 3).

Color vision deficiency is usually diagnosed with Ishihara Color Plates (Figure 8; Figure 9). The test consists of a pattern made up of multicolored dots. If color deficiency is not present, the normal eye should see numbers and shapes among the dots; however, color-blind patients will have difficulty finding the number or shape in the pattern.[11,18]

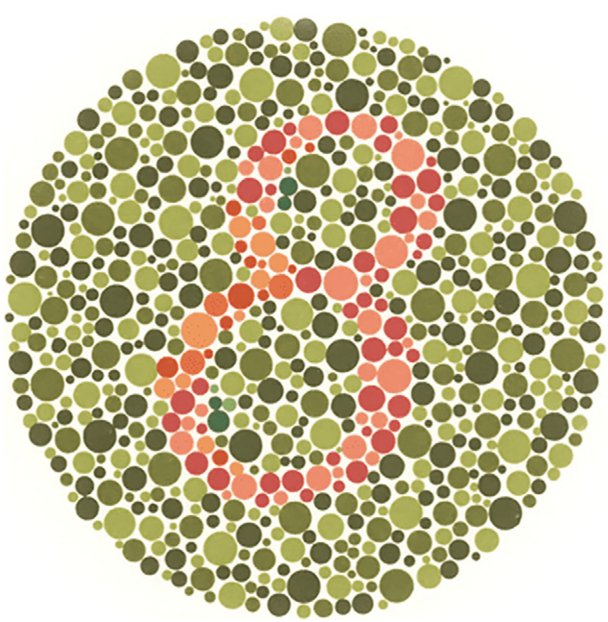

Fig. 8 Ishihara Plates 1. Source: own photo.

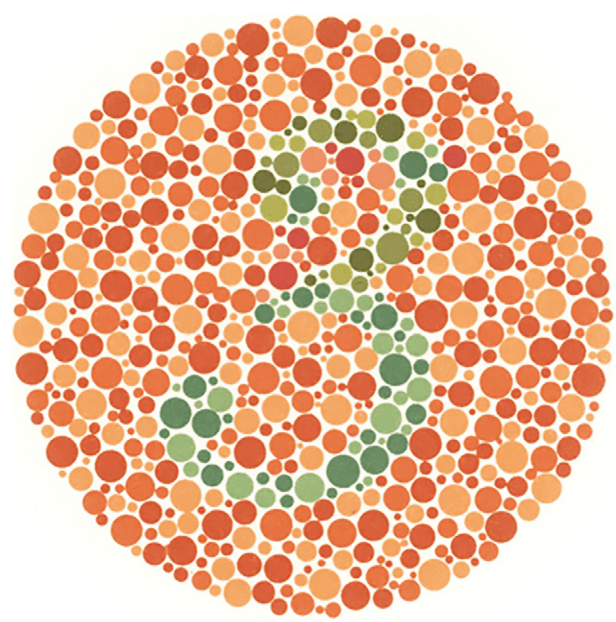

Fig. 9 Ishihara Plates 2. Source: own photo.

Although currently there is no cure for color blindness, there are four registered clinical trials for gene therapy in achromatopsia. In these trials, patients receive an adeno-associated virus capsid with the human transgene driven by cone-specific promoter fragments by subretinal injection after vitrectomy. All trials are in phase I/II. The trials are designed to initially check the safety profile of the subjects who are 18 years or older and also include visual acuity, electrophysiology, and color vision function.

In one of the four trials registered for achromatopsia, patients received intraocular implants that released ciliary neurotropic factor. Unfortunately, there was no improvement in cone function. As a result, plans to include ciliary neurotropic factor in any registered clinical trials involving human genes have been abandoned.[17]

Color vision deficiency might limit and influence some professional activities for commercial or air force pilots, electricians, defense forces including paramilitary, food and art critics, and some physicians, scientists, and engineers. For example, full color vision is required for a pilot license. Air traffic controllers are currently working on color computer screens instead of black and green radar displays, and airline pilots now rely on color displays for electronic onboard instruments as well as signal lamps.[19]

Color-coding is most often used to reinforce a message mainly transmitted by alphanumeric or symbolic coding. For electricians, the surface color is the only or primary means of communication. An example may be a color code indicating the values of resistors and capacitors or the color of specific cables.[19] Illustrative of this was a 1940 Time magazine story: the Army Air Corps watcher was able to detect only ten of 40 camouflaged artillery items on earth. The Field Artillery Observer on the plane noticed all 40 and precisely marked positions on the map. It turned out that the artilleryman, chosen on the basis of a less rigorous examination than the soldier from the Army Air Corps, was color-blind.[20]

Camouflage, designed to fool the normal eye, did not provide protection with the color-blind person. Surface color conveys information to determine fruit maturity, freshness of food, or properly cooked meat.[19] Perfect or good color vision is not yet a precondition for any medical jobs.

Compromised color vision can be a problem in medicine. The terminology of some diseases, when their etiology was unknown, was determined by the color of the most visible changes. Blackwater fever, malignant melanoma, and albinism are just exemplary names of diseases or signs whose medical terminology has been associated with the color.[21]

Meaning of colors in different cultures

Colors play an important role in many aspects of life. They relate respectively to the body, the mind, and the emotions. Color has long been used to create feelings. Light and color can influence how people perceive the area around them. They can remind one of a place, a time of year, or favorite traditions. Carl Jung (1875-1961) is associated with the pioneering stages of color psychology. Jung was most interested in properties and meanings of color, as well as in potential of art as a tool for psychotherapy. Jung attempted to unlock and develop a language of colors. He looked to alchemy to further his understanding of the secret language of color, finding the key to his research in alchemical transmutation. When it comes to what different colors symbolize in cultures around the world, these associations can vary greatly.

Red

In some European cultures, red may have negative meanings, such as defiance, aggression, visual impact, and strain. In Indian culture, red is known as the most powerful of all colors, where physical courage, strength, warmth, energy, basic survival, stimulation, masculinity, and excitement are just examples of the meanings conveyed by red. A married woman's hands are decorated with red henna, and a red powder is used along the hairline.[22,23]

South Africans associate red with mourning, and the red color in the country's flag symbolizes violence and sacrifices that were made during the struggle for independence.[24] In Thailand, red is the color associated with Surya, the god of solar energy, who was born on Sunday. This explains why on this day, as well as on the birthday, red is the dominant color.[25] In Chinese culture, red represents a celebration and is believed to bring happiness, prosperity, and a long life. The Chinese wear it for the New Year, as well as during funerals and weddings.[25]

Yellow

Yellow is related in some European cultures with a positive meanings, including optimism, confidence, self-esteem, extraversion, emotional strength, friendliness, and creativity.[26] This color suggests a warm, cheery feeling, although yellow has some darker meanings in other cultures, such as irrationality, fear, emotional fragility, depression, anxiety, or suicide.

In France, as well as in Germany, yellow signifies jealously[26]; other meanings are betrayal, weakness, and contradiction. The doors of traitors and criminals were marked yellow during the 10th century in France.[27]

In China, yellow is associated with pornography.[23] In Africa, yellow is reserved for the highly ranked due to its close resemblance to gold, which is universally associated with money, quality, and success. Similar situations may be found in Egypt, where yellow has been associated with gold.

From 1387 and the War of Dynasties in Japan, yellow has represented bravery, wealth, and refinement. During this time, warriors wore yellow chrysanthemums to represent the emperor, and royal family displayed yellow as a pledge of courage.[28]

In Thailand, yellow is the lucky color for Monday, because Bhumibol (1927-2016), the King of Thailand, was born on that day. To pay tribute to the king, many Thais wear yellow on Mondays.[23,25]

Blue

In Western culture, blue has some positive meanings, including intelligence, communication, trust, efficiency, serenity, duty, logic, coolness, reflection, and calm. Sometimes, it has some negative meanings, including coldness, aloofness, lack of emotion, and unfriendliness. It can also be negative, indicating feelings of melancholy. It also symbolizes trust, security, and authority.

Its calming effect explains why some banks have used this color in their logos. Blue is a symbol of masculinity except in China, where it is considered a feminine color. In many Middle Eastern countries, blue is used to provide security and protection, symbolizing heaven, spirituality, and immortality. For Catholics, blue is a sign of hope and good health. That is why the Virgin Mary is often depicted in a blue robe. In Judaism, blue is associated with holiness and divinity. In Hinduism, blue conveys not only love and joy, but also may diminish pain and sin, being the color of Krishna.[23]

Green

Green in Western civilizations has some positive meanings, including harmony, balance, refreshment, universal love, rest, restoration, reassurance, environmental awareness, equilibrium, and peace; it rarely has some negative meanings, including boredom, stagnation, blandness, and enervation. Green is often associated with nature and environmental awareness. At the same time, it has been a military color.

Green may suggest the spring, freshness, inexperience, jealously, greed, and the Christmas tree. Green is the national color in Ireland due to Saint Patrick, where it is associated with good luck, leprechauns, and shamrocks. Most Eastern and Asian cultures relate to green as a new and eternal life, new beginnings, fertility, youth, health, and prosperity. Mexico displays green in its flag to represent independence after gaining freedom from Spain, whereas in Spanish-speaking South American countries, green has a negative meaning and symbolizes death.[23,29]

Purple

Purple is usually related to royalty, wealth, power, exclusivity, and fame. The genesis of this meaning concerns purple dye that was difficult to produce, as it was extracted from sea snails. Purple clothing was very expensive, and so royalty wore it. In many European countries, as well as in Brazil, Thailand, and India and among many Catholics, purple symbolizes death. In Thailand and Brazil, purple, like black, is worn in mourning. In the United States, soldiers who have shown incredible courage and honor are decorated with the Purple Heart.[23,29]

Orange

Orange, depending on the context and culture, is associated with some positive meanings, including physical comfort, food, warmth, security, sensuality, passion, abundance, and fun. There are some negative meanings, including deprivation, frustration, frivolity, and immaturity. Orange is the national color in the Netherlands and represents the Dutch Royal family. In many additional Western cultures, orange represents curiosity, innovation, and creativity, whereas in Egypt, orange is associated with mourning.

After the Orange Revolution, this color became a symbol of strength and bravery in the Ukraine, representing a time when the country came together in 2004 and rebelled against the government during one of the biggest fraudulent presidential elections in history. In Japan and China, orange is a color of courage, love, happiness, and good health. The orange-colored spice, saffron, is considered to be both a good omen and sacred.[23]

Perceptions of color

Although the physical nature of color is well understood and is based on different wavelengths, its perception in humans and animals is more speculative and is based on different concepts. Because color is commonly found in various forms of organic and inorganic materials, the life of humans and different animals has been based on appropriate color recognition and discrimination. Colors have different meanings in various cultures.

In medicine, healthy structures have their natural color, and it is often changed during pathologic conditions. In many conditions, these color changes have been found to have characteristic features for distinguishing various diseases. Illustration of this concept includes the name *anthrax* that comes from the Greek word for coal, possibly coming from the Egyptian etymology, due to the characteristic black skin lesions developed by persons with a cutaneous anthrax infection. A *xanthoma*, from Greek meaning “yellow,” is a deposition of yellowish cholesterol-rich material that can appear anywhere in the body in various disease states. The word *melanoma* came to English from the Latin and uses combining forms derived from ancient Greek roots: *melano-* (denoting melanin, “dark”) + *-oma* (denoting a tissue mass, and a “process”). *Jaundice* comes from the French *jaune,* meaning “yellow,” and *jaunisse* meaning “yellow disease.” The term *icterus* is from Greek. *Leukemia* was initially described by Rudolf Virchow, who called the condition *Leukämie* in German, which he formed from the two Greek words *leukos,* meaning “white,” and *haima,* meaning “blood.”

Conclusions

Dermatology is probably the most color-dependent medical specialty. Color vision deficiencies may well limit the ability of the physician to distinguish between different hues or even colors in several clinical situations.

References

1. Purves D, Augustine GJ, Fitzpatrick D, et al. *Functional Specialization of the Rod and Cone Systems Neuroscience. 2nd ed. Sunderland, MA.* Sinauer Associates. 2001.
2. Narloch A. Categorization and color perception. *Scripta Neophilologica Posnaniensia* 2016;XVI:69-83.
3. Schmitz H, Schmitz A, Bleckmann H. A new type of infrared organ in the Australian "ire-beetle" Merimna atrata (Coleoptera: Buprestidae). *Naturwissenschaften* 2000;87:542-545.
4. Tri Hoang Do M, King-Wai Y. Intrinsically photosensitive retinal ganglion cells. *Physiol Rev* 2010;90:1547-1581.
5. Graham DM, Wong KY. Melanopsin-expressing, intrinsically photosensitive retinal ganglion cells. In: Kolb H, Fernandez E, Nelson R, eds. Webvision: The Organization of the Retina and Visual System. Salt Lake City, UT: University of Utah Health Sciences Center; 2008.
6. Ecker JL, Dumitrescu ON, Wong KY, et al. Melanopsin-expressing retinal ganglion-cell photoreceptors: cellular diversity and role in pattern vision. *Neuron* 2010;67:49-60.
7. Sherman PD. *Problems in the Theory of Perception of Colour: 1800-1860.* London, England: Thesis presented for the Degree of Doctor of Philosophy in the Field of History of Science. October 1971.
8. Mollon JD. *The Origins of Modern Color Science.* London: England; Elsevier Ltd. 2003.
9. Lee BB. The evolution of concepts of color vision. *Neurociencias* 2008;4:209-224.
10. Svaetichin G. Spectral response curves from single cones. *Actaphysiol Scand Suppl* 1956;39:17-46.
11. Kalloniatis M, Luu C. In: Kolb H, Fernandez E, Nelson R, eds. Webvision: The Organization of the Retina and Visual System. Health Sciences. Salt Lake City, UT: University of Utah; 2005. p. 923-949.
12. Brown PK, Wald G. Science: visual pigments in single rods and cones of human retina. Direct measurements reveal mechanisms of human night and color vision. *Science* 1964;144:45-52.
13. Marks WB, Dobelle WH, Macnichol EF. Visual pigments of single primate cones. *Science* 1964;143:1181-1183.
14. Turner RS. *In the Eye's Mind: Vision and the Helmholtz–Hering Controversy.* Princeton, NJ: Princeton University Press. 1994.
15. Adams EQ. A theory of color vision. *Psychol Rev* 1923;30:56-76.
16. Haegerstrom-Portnoy G, Schneck ME, Lott LA, et al. Longitudinal increase in anisometropia in older adults. *Optom Vis Sci* 2014;91:60.
17. Hassall MM, Barnard AR, MacLaren RE. Gene therapy for color blindness. *Yale J Biol Med* 2017;90:543-551.
18. Facts About Color Blindness. Available at: https://nei.nih.gov/health/color_blindness/facts_about. Accessed December 14, 2018.
19. Cole BL. The handicap of abnormal colour vision. *Clin Exp Optom* 2004;87:258-275.
20. National Defense: Color-Blind Observers. Available at: http://content.time.com/time/magazine/article/0,9171,772387,00.html. Accessed December 14, 2018.
21. Durkalec J, Hasik J. Color in medical terminology. *Nowiny Lekarskie* 2000;69:652-655.
22. Jurek K. The symbolic meaning and functions of the color in the culture. *Kultura Media Teologia* 2011;6:68-80.
23. Briggs O. What colors mean in other cultures. Available at: https://www.huffpost.com/entry/what-colors-mean-in-other_b_9078674. Accessed December 14, 2018.
24. Banton M. *Anthropological Approaches to the Study of Religion.* London, England: Psychology Press. 2004:47-59.
25. Tien-Rein L. The color we use in our daily life - communicating with color. Presented at: Asia Colour Association Conference 2013: Blooming Color for Life. December 11-14; 2013:22-25. Thanyaburi, Thailand
26. Hupka RB, Zaleski Z, Otto J, et al. The colors of anger, envy, fear, and jealousy. *J Cross-Cultural Psychol* 1997;28:156-171.
27. Eiseman L. Colors for Your Every Mood: Discover Your True Decorating Colors. *Sterling, Capital Books* 2000;46.
28. Morton J. Yellow – The Meanings of Yellow. Available at: https://www.colormatters.com/the-meanings-of-colors/yellow. Accessed Dec 14, 2018.
29. Swallow D. Meaning of colours across cultures. Available at:http://www.deborahswallow.com/2010/02/20/meaning-of-colours-across-cultures/. Accessed December 14, 2018.