

DICHROMATISM

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1. Core Definition

Dichromatism, or dichromacy, refers to a form of severe partial color blindness characterized by the presence of only two types of functional cone photopigments in the retina, rather than the three types found in individuals with normal color vision (trichromats). This condition profoundly limits the ability of the affected individual to discriminate between various hues, as their perception of the visible spectrum is fundamentally collapsed along a specific dimension. While standard human color vision relies on the differential stimulation of long-wave (L), medium-wave (M), and short-wave (S) sensitive cones to perceive the full range of colors, the dichromat must rely solely on the ratio of signals derived from the two remaining functional cone types.

The practical consequence of this physiological limitation is a significant reduction in the color space available to the individual. Where a trichromat perceives a complex interplay of three primary colors (typically red, green, and blue), the dichromat perceives the world along a single axis of color variation, often described as shades of blue/yellow or red/green, depending on which cone type is missing or non-functional. For example, individuals lacking the M-cone pigment struggle to distinguish red from green, leading to confusion between these hues, which appear to them as similar shades of yellow or neutral colors.

It is crucial to differentiate dichromatism from other forms of color vision deficiency, such as anomalous trichromacy (an abnormality where all three cone types are present but one has a defective spectral sensitivity, leading to reduced, but not absent, color discrimination) and monochromacy (the complete absence of color vision, relying only on rods or one cone type). Dichromatism represents a complete loss of one dimension of color perception, making it a notably more severe impairment than anomalous trichromacy, yet still allowing for basic discrimination based on the remaining two channels.

2. Biological Basis of Color Vision and Trichromacy

Normal human color vision, or trichromacy, is achieved through the interaction of three distinct classes of retinal photoreceptor cells known as cones. Each cone class contains a unique visual photopigment (opsin) tuned to absorb light optimally at different wavelengths. The S-cones are maximally sensitive to short wavelengths (blue/violet), the M-cones to medium wavelengths (green), and the L-cones to long wavelengths (yellow/red). The brain interprets color by comparing the relative rates of absorption across these three channels. This comparative process allows for the perception of millions of distinct hues.

The genetic underpinnings of these pigments are well-established. The gene coding for the S-cone opsin is located on Chromosome 7. In contrast, the genes for the M-cone and L-cone opsins are situated closely together on the X chromosome. This genetic localization is highly significant, as mutations or deletions affecting these X-linked genes are the primary cause of the most common forms of dichromatism (protanopia and deuteranopia), explaining why these conditions are overwhelmingly more prevalent in males. The functionality of these opsins is essential; if one opsin is absent or severely non-functional, the input signal from that specific color channel ceases, resulting in dichromatism.

In dichromatism, the fundamental requirement for comparing three independent signals cannot be met. The visual system receives input from only two channels, which means that any two colors that stimulate the remaining two cone types in the same ratio will be perceived as identical, regardless of their actual spectral composition. This concept is formalized by the principle of univariance in vision science, illustrating why dichromats experience 'color confusion' along an axis--they possess only a single neutral point (a specific wavelength they perceive as achromatic or white/grey), whereas trichromats rely on the balanced stimulation of all three cone types to perceive white.

3. Classification and Types of Dichromatism

Dichromatism is traditionally categorized into three primary types, defined by which of the three cone photopigments is missing or non-functional. These categories are crucial for accurate diagnosis and understanding the specific spectral limitations faced by the affected individual. The two most common forms, protanopia and deuteranopia, are related to the L and M cone systems, while tritanopia, the rarest form, involves the S cone system.

Protanopia occurs when the long-wavelength sensitive cones (L-cones) are either absent or fail to produce functional photopigment. Because the L-cones are critical for perceiving reds and high-luminance colors, protanopes experience two major effects. First, they cannot distinguish between reds and greens (the red-green confusion axis). Second, they experience a dimming effect for red light, as their remaining M-cones are less sensitive to the far-red end of the spectrum compared to the missing L-cones. For a protanope, deep red colors may appear very dark or black.

Deuteranopia is characterized by the absence of functional medium-wavelength sensitive cones (M-cones). Like protanopes, deuteranopes also suffer from red-green color confusion, as the M-cones are necessary for differentiating these hues. However, unlike protanopes, deuteranopes do not experience the same severe loss of brightness for red light, as their L-cones remain functional. This difference in luminosity perception is the key feature distinguishing protanopia from deuteranopia, although their confusion axes are nearly identical in terms of hue.

Tritanopia is significantly less common than the X-linked forms and involves the absence of

functional short-wavelength sensitive cones (S-cones). Tritanopes struggle to distinguish colors along the blue-yellow axis. Blues and yellows are confused, and their visual world is often described as shades of red and green. Unlike protanopia and deuteranopia, tritanopia is inherited via an autosomal dominant pattern (Chromosome 7) and affects males and females with roughly equal frequency, often associated with specific diseases or acquired later in life due to ocular conditions.

4. Genetic and Physiological Causes

The vast majority of dichromatic cases, specifically protanopia and deuteranopia, are inherited as X-linked recessive traits. Because males possess only one X chromosome, a single defective gene copy on that chromosome is sufficient to express the condition. Females, having two X chromosomes, must inherit the defective gene on both X chromosomes to be dichromatic, making the disorder extremely rare in women. However, women can be asymptomatic carriers of the trait, potentially passing it on to their sons. This pattern of X-linked inheritance underlies the high prevalence of red-green color deficiency in the male population (around 8%).

The underlying molecular mechanism typically involves deletions, inversions, or point mutations within the opsin gene cluster on the X chromosome. Given the high degree of homology and close proximity of the M and L cone opsin genes, they are susceptible to unequal crossing over during meiosis. This genetic error can lead to the complete deletion of one gene (resulting in dichromatism) or the formation of a hybrid gene (resulting in anomalous trichromacy, where the spectral sensitivity is shifted). In protanopia, the L-opsin gene is non-functional or missing; in deuteranopia, the M-opsin gene is affected.

Tritanopia, being autosomal, arises from mutations in the gene encoding the S-cone opsin on Chromosome 7. While congenital tritanopia is rare, acquired dichromatism that mimics tritanopia symptoms (blue-yellow confusion) is more common. Acquired color vision deficiencies are typically caused by diseases affecting the optic nerve or retina, such as glaucoma, diabetic retinopathy, or the side effects of certain medications, where the damage specifically impacts the blue-sensitive pathways more severely.

5. Diagnostic Methods and Prevalence

Diagnosis of dichromatism is primarily achieved through standardized color vision tests designed to reveal specific color confusions. The most widely recognized screening tool is the Ishihara test, which consists of a series of pseudoisochromatic plates containing colored dots forming numbers or patterns. Dichromats struggle to distinguish the figure from the background because the colors used fall along their specific confusion axis. For instance, red-green dichromats cannot discern figures based on the contrast between red and green dots.

While the Ishihara test is excellent for screening, more sophisticated instruments are necessary to precisely classify the type and severity of the deficiency (dichromacy vs. anomalous trichromacy). The anomaloscope is considered the gold standard. This device requires the patient to match a test color (usually a spectral yellow) by mixing two primary colors (typically red and green). A protanope or deutanope will accept matches significantly outside the range accepted by a normal trichromat, often matching pure red or pure green to the spectral yellow, depending on the missing pigment.

The prevalence of dichromatism varies significantly by type and gender. Protanopia and deutanopia combined affect approximately 1-2% of the male population globally, with deutanopia being slightly more common than protanopia. Due to the X-linked nature, the prevalence in females is dramatically lower, estimated to be less than 0.01%. Tritanopia is rare, affecting only about 1 in 50,000 individuals, and shows no gender bias due to its autosomal inheritance. The high prevalence of red-green dichromatism necessitates its consideration in fields ranging from public safety to educational curriculum development.

6. Significance and Impact on Daily Life

The functional impact of dichromatism is significant, influencing numerous aspects of daily life, vocational choices, and safety. Because color signals are ubiquitous in human communication and warning systems, dichromats face challenges in interpreting traffic signals, maps, color-coded graphs, and warning labels. For red-green dichromats, the typical red/green traffic light configuration requires reliance on position (top for red, bottom for green) rather than color alone, a strategy that fails in horizontal or unusual light placements.

Vocational restrictions are imposed in many industries where accurate color discrimination is critical, including aviation, naval operations, electrical engineering (reading color-coded wiring), medical diagnostics (interpreting lab results), and textile manufacturing. While individuals with dichromatism often develop sophisticated compensatory mechanisms based on brightness cues and textural information, these adaptations are rarely sufficient to meet the stringent safety requirements of certain highly color-dependent professions.

In social and educational contexts, dichromatism can lead to misunderstandings or difficulties. Children may struggle with color-based learning materials or artistic assignments. However, modern technology, including specialized color filters, applications that label colors, and accessibility settings on devices, is increasingly mitigating these daily challenges. Furthermore, the study of dichromatism has provided crucial insights into the mechanisms of color perception, helping scientists understand how the brain constructs color from differential cone input.

7. Current Research and Theoretical Context

Research in dichromatism continues to inform broader theories of color vision and perception. One key area of study involves the contrast with tetrachromacy, a condition hypothesized to exist in some human females who, as carriers of X-linked color deficiencies, might possess four functional cone types. If a female carries one normal X chromosome and one X chromosome containing a slightly shifted opsin gene, she theoretically possesses four distinct channels of color information, potentially leading to a richer color experience than normal trichromats. The existence and functional perception capabilities of human tetrachromats provide a conceptual counterpart to the reduced capabilities of dichromats.

Another active research frontier is gene therapy. Since the genetic basis of many forms of dichromatism is known, scientists have explored using viral vectors to introduce the missing functional opsin gene into the retinal cells of dichromatic individuals. Landmark studies in non-human primates suffering from dichromatism have successfully restored trichromatic vision by introducing the missing gene, demonstrating the potential for reversing the condition. While human trials face safety and ethical hurdles, these advances offer hope for future therapeutic interventions that could restore full color perception to dichromats.

Furthermore, dichromatism serves as a powerful model in neuroscience for understanding the plasticity of the visual cortex. Studies investigate how the brain adapts to the missing sensory input and whether the remaining neural pathways reorganize themselves to maximize the use of the available two color channels. This research is vital not only for treating color blindness but also for understanding how sensory deprivation shapes cortical development and adult neural function.

Further Reading

[Dichromacy - Wikipedia](#)

[Cone Cell - Wikipedia](#)

[Protanopia - Wikipedia](#)

[Deuteranopia - Wikipedia](#)

[Ishihara Test - Wikipedia](#)