On the Spectral Dimensionality of Subject Colors

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Annotation

Three dimensions of aperture color do not suffice some professional applications of color imaging. To improve metameric and low-illumination subject colors, a fourth spectral channel in color films and the multi-spectral systems in the electronic imaging are designed. To evaluate the dimensionality, a mathematical simulation has been performed on the base of the optical mechanism for single-pigment intrareceptor color opponency, which explained color phenomena, inconsistent with the common RGB-cones opponency models. Recent data on the two anatomical parts of outer segment of rod or cone and the spectra of long-living photoproducts at the human body temperature allowed to detect five spectral ranges independently affecting color hues within a wide illumination range. The rhodopsin partial receptors (505 and 535 nm) in the rod perform the yellow-blue separation in the two differential sensitivity ranges parted by the neutral point of protanope or deuteranope at 495 nm. The partial receptors (560 and 610 nm), based by the cone photopigment, did the green-red separation in the three ranges of visible spectrum parted by the neutral points of tritanope at 460 and 575 nm. At least a fourth independent channel has been shown to be required to provide simultaneously all of the colors in a scene for the spectrally-correct reproduction.

Introduction

No imaging system perfectly reproduces for the present all of the subject colors in the same image. The three dimensions of aperture color do not suffice color imaging, especially in rendering low-illumination and metameric subject colors.[1-6] An issue is the increased color saturation that is preferred in the three-dimensional imaging but cannot actually solve the problem.[1] Even two spectral ranges independently recorded could render most of the main color hues in an image low-saturated.[7] To substantially improve the subject colors, a fourth independent spectral channel in modern color photographic films[2,3] and the multi-spectral recording in the electronic imaging systems are designed.[4-6]

To render the metamery, an imaging system has to accurately record and represent their spectra as they are perceived by human photoreceptors. The channel sensitivities of imaging system should close to that of vision receptors. Even if the color reproduction of photographic films is one of the most sophisticated, their spectral sensitivities[2,3] are far from those of standard colorimetric observer,[8] some arbitrarily chosen[9] vector rotations of spectral sensitivities of human vision at different conditions.

"Among intermediate colors, blue-green, purple and magenta-red colors are very important for professional portrait because those colors are very common in European and Japanese clothes... The reproduction of these colors is difficult to achieve in silver halide photography".[2] Neither spectral sensitivity shifts nor interimage effects improve the colors without worsening the reproduction of the primary colors. "In many current commercial films: (1) violet: shifted to red direction; (2) teal-green: shifted to blue direction; (3) crimson and wine-red: reproduced as red color, and (4) clear and dark spheres of red rose or red dress reproduced as the same chroma... Shift to shorter wavelengths of red sensitive layer led to decrease in chroma of red color. Usually, enhancement of interimage effect makes up for the decrease in chroma. This technology solved the decrease in chroma of primary colors, but it caused damages of correct intermediate color reproduction."

Only with using "the new design concept of 'dependency of spectral sensitivity shift on different exposure range', ...it became possible to reproduce correct intermediate colors which were difficult to reproduce in silver halide photography without decrease in chroma of primary colors."[2] The approach[3] involves a fourth spectral channel at low exposures where the inefficiency of three-channel rendering is most obvious. It is the exposure dependency that appears to hinder to use the extra channel most efficiently.

Multispectral approach,[4-6] which uses much more channels to record the subject spectra, is another reaction on the "problems of metamerism",[5] insoluble within the scope of the three-channel paradigm.

The mechanism for single-pigment two-color opponency in a human photoreceptor,[9-11] which successfully explained the principal inconsistencies of current theories of color perception,[11] is used below to estimate the actual spectral dimensionality of subject colors and the spectral sensitivities of the partial photoreceptors of human color vision that produce the basic color impressions.

Spectra of Opponent Color Receptors

Human color vision separates colors in two basic complementary pairs: blue-yellow and green-red.[12-15] The three-dimensionality of aperture color corresponds to four independent basic spectral channels of the four basic color responses. The basic yellow color impression is independent of the basic green and red impressions: it is seen by protanopes and deuteranopes lacking the two latter basic colors and is not seen by tritanopes that see only the green-red opponent pair.[16,17] The yellow is not seen by the normal central fovea that has no rods, whereas the only yellow-blue opponent pair is seen by the normal peripheral vision performed predominantly by the rods.[18] The only yellow-blue pair is seen closer to the fovea with decreasing illumination.[19] In this case, the chroma of an aperture color is characterized by the two differences of basic opponent colors, and its lightness by their sum. Nevertheless, the number of independent spectral sensitivity ranges, producing the basic opponent color impressions, is four.

The data suggests that the basic yellow is not and cannot be a sum of the complementary impressions (their sum has to be a gray) produced by the hypothetical 'green' and 'red' cones as suggested by the after-receptor mechanisms for the opponent color separation.[15] The spectral ranges of four partial receptors of human color vision may be estimated on the base of computer simulation of the optical mechanism for single-pigment intra-receptor color opponency described in detail in Ref. 11. The recent data on the two anatomical parts of light-sensitive outer segment of rod or cone[20-25] and the spectra of photoproducts long-living at the human body temerature[11,26] has allowed to estimate the differential spectral sensitivities of partial opponent receptors in the rod and cone, which independently affect the color rendering within an extensive illumination range.[11]

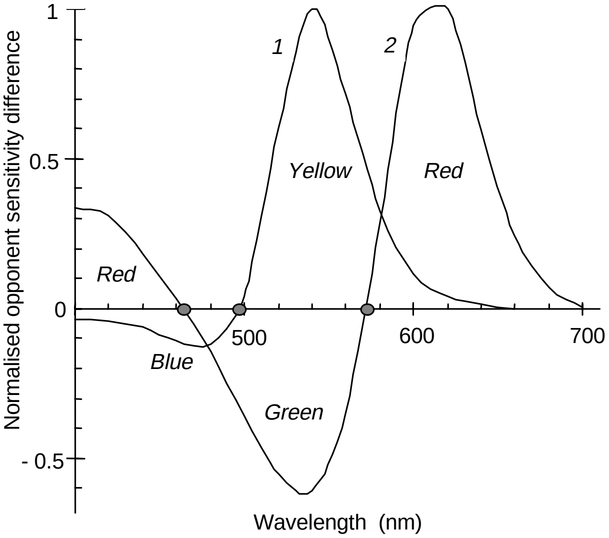

Figure 1. The opponent differences of the relative partial spectral sensitivities in the rod (1) and cone (2). The gray circles denote the neutral points of the photoreceptors. The spectral absorption of other eye elements is not taken into consideration.

The rhodopsin partial receptors in the rod have the spectral sensitivity maxima at 505 and 535 nm.[11] They perform the blue-yellow separation in the two ranges of differential sensitivity parted by the neutral point of protanope or deuteranope at 495 nm. The partial receptors on the base of iodopsin-like cone photopigment have their spectral sensitivity maxima at 560 and 610 nm. They perform the green-red separation in the three ranges of visible spectrum parted by the neutral points of tritanope at 460 and 575 nm.

The receptors perceive independently four spectral ranges (see Fig. 1) that produce the four basic color impressions. Those separated in the rod (curve 1) are: 400 to 495 nm, which produces the blue basic impression, and 495 to 650 nm, which produces the yellow basic impression. The blue basic hue corresponds to 460 nm and the complementary basic yellow hue does to 575 nm as seen undistorted only at the neutral points of the cone. The spectral ranges separated by cone (curve 2) are: 460 to 575 nm, which produces the basic green, and a complex spectral range consisting of two parts, 400 to 460 nm and 575 to 750 nm, which produce the basic red impression. The green basic hue corresponds to 495 nm, the neutral point of the rod, and the complementary basic red hue is seen with varying saturation after 650 nm where the rod is practically insensitive. The curves are close to those obtained by different methods in Ref. 13,14 and to the opponent potential responses of single photoreceptor cells that were first measured by G. Svaetichin[27] in a strongly illuminated teleost retina.

The basic opponent hues are seen at the characteristic wavelengths above not with their highest saturation: they are undistorted in the spectral points, such as neutral points of dichromates, or within the spectral regions where another receptor cannot contribute a chromatic impression. The sensitivity difference curves 1 and 2 reflect the spectral dependence of saturation of basic hues. If the saturation dependencies are known quite accurately, every color is a mixture of two of the four basic hues, with their saturation at a wavelength, or averaged within a spectral range considered. Its brightness is determined by the sum of spectral sensitivities of the rod and cone.[11]

A spectrally true imaging system should at least to record independently the four spectral signals and transform them into a form, which could induce in the eye the independent basic impressions of blue or yellow, and green or red. Land[7] showed two spectral ranges to roughly render main image color hues even if low-saturated and substantially distorted. The current imaging systems independently record only three spectral ranges bound with the blue, green and red basic impressions. They roughly replace the fourth independent spectral range, bound with the yellow basic color, with the sum of the ranges, bound with the green and red basic colors. That makes impossible the further improvements in subject colors with only a spectral shift of the three ranges or the saturation increase by inter-image effects in a color photographic film.

This explains why the imaging systems need the fourth color channel and why it is especially helpful at low illumination. The green and red spectral channels cannot efficiently substitute the yellow one in usual color films or printing systems. The blue-yellow opponency mechanism works on efficiently when the green-red one is already out.[19]

To reproduce accurately metameric colors of different spectral composition is a main challenge for current and prospective imaging systems and their interactions. With taking into account the opponent properties of human color vision, the problem appears to have a finite solution only in four-dimensional space.

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Biography

Vitali V. Gavrik got his first-class honors M.S. degree from the Leningrad Institute for Cinematography Technologies, joined the Federal Research Center "S. I. Vavilov State Optics Institute" in St. Petersburg (Russia). Run the Laboratories for System Investigations in Photography and for Image Research. Obtained results of fundamental importance in the fields of perceptual image quality, human color vision, optics and physical chemistry of imaging processes. Got his Ph.D. in Imaging and D.Sc.Phys.-Math. in Optics from the FRC. Over 70 scientific publications.