WHAT COLOUR IS

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A definition of colour as ratios of cones' stimulation functions is proposed. Gauss functions are chosen as model for these functions. The definition explains features of human colour vision without any additional assumptions. The opponent pairs of colours: red-green and yellow-blue are the result, not the principle of colour vision.

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1. Introduction

It is not very difficult to take a nice colour photography but to take a good black&white picture is art. People are less particular about colourful pictures. The world without colours seems to be boring and sad. Colours are also a part of special language in Nature — one can learn it from behaviour of animals.

The above reasons, and probably many more, cause that colours are subject of physicists', biologists', psychologists' and artists' investigations. Each of these groups has their own questions: how one can copy particular colour, what is human psychological reaction to hues, which neurons/parts of brain take part in colour detection.The question this article is focused on is what colour is.

When light reachs an eye it goes through optic system of the eye and may be absorbed in the retina. Vertebrates' retina contains five main groups of cells: photoreceptors, horizontal cells, bipolar cells, amacrine cells and ganglion cells [1–4]. Human retina, on which this article is focused, has four types of photoreceptors: very sensitive rods and three types of less sensitive cones. Photoreceptors absorb light, convert the energy of a stimulus into neural impulses and send signal farther. Bipolar and next ganglion cells transmit cones' signals in the direction perpendicular to the surface of the retina. Amacrine and horizontal cells connect and influence these paths sending information parallel to the retina's surface. These parallel pathways are a way for encoding information in the retina. One of the results is that only part of ganglion cells are colour sensitive. Axons of ganglion cells compose optic nerve and the retina's output.

2. Short history of colour vision research

In 1665 Isaac Newton proved that white light (sunlight) is composed of colours of rainbow. On the turn of the eighteen century the idea of colour trichromancy in human vision was postulated [5, 6] and verified [7]. Human colour vision may be described with three independent variables. In parallel the concept that trichromancy results from physiology of the eye and not from physical properties of light was being developed [8–10]. Three response systems were identified as three photoreceptor cells: the short-, middle-, and long-wave sensitive cones (S-, M-, L-cones respectively). Their absorption spectra were measured [11–13] (for references see also [4]).

More than one type of photoreceptor is one of the colour vision necessities. The mechanism for comparing outputs of different types of cones' is the second requirement. In 1878 Ewald Hering [14] proposed that two opponent processes: red-green and yellow-blue take place after light detection. This idea exists up to this day.

3. Cones' stimulation functions

Nowadays it is known that colour exists only in our minds. It is the map we put on the outer world to characterize different objects. It is also known that one type of photoreceptor is able to distinguish between light and dark areas only [1]. Primates colour vision is based on three types of photoreceptors: L-, M- and S-cones [1, 4, 12, 15]. Now their activity spectra are well-known [4, 12, 13] as well as their distribution in the retina [15, 16].

Let us omit the problem of edges and movement detection and focus on a surface that is projected on a cone layer in the retina. All information the brain gets is coded as the set of three quantities, three cone stimulations. Let us denote them by

$$(P_{\mathrm{L}}\ ,\ \ P_{\mathrm{M}}\ ,\ \ P_{\mathrm{S}})\,. \tag{1}$$

These three quantities, together with size and shape, are all the information the brain can get about any object and it is these three numbers that we name a colour.

We can find a model function for cone spectral sensitivity from an experiment. Using published data [12] we have chosen as the model Gaussian functions

$$P_x(\lambda) = c_x e^{-\frac{2(\lambda-\lambda_x)^2}{{\sigma_x}^2}}\,, \qquad x = \mathrm{L,M,S}\,, \tag{2}$$

where λ is the wavelength. Wald in [12] put up two sets of data. First of all he measured spectral sensitivities *at the corneal level.* This data were further modified by regarding ocular and macular absorbancies. It resulted in spectral sensitivities *at the level of the cones.* The ocular and macular absorbancies are meaningful only for the short-wavelength part of the visible spectrum, so the curves become asymmetrical. Since we are interested in an *effective* sensitivity of receptors, related to a beam of light that reaches an eye, we have used the directly measured sensitivity of cones *at the corneal level.* The Gauss function as a model for these dependences seems good enough (χ^2 test gave values no bigger than 0.001 in all cases).

We also assume that the response of a cone to a stimulus is proportional to the intensity of the light. Finally we get

$$P_x = c_x \int\limits_{\mathrm{vs}} I(\lambda) e^{-\frac{2(\lambda-\lambda_x)^2}{{\sigma_x}^2}} d\lambda, \qquad x = \mathrm{L,M,S}\,, \tag{3}$$

where the integration is over the visible spectrum (*vs*) and $I(\lambda)$ is the intensity of light that reached the eye.

4. Brightness and hue

When level of luminosity is low enough only one type of the receptors (rods) work [1,4] and we can see darker and lighter objects. One can say that we can see only one colour or that we cannot see any colours at all. Since black and white world is familiar for people it seems natural to divide the above general notion of colour into brightness and hue. So, at this moment, we introduce the difference in meaning between words colour and hue. Each colour has two features, *brightness* and *hue.*

Brightness should depend on all three P_x (even if S-cones are meaningfully less sensitive than L- and M-cones). The simplest choice is a sum of three P_x

$$\boldsymbol{b} = \sum_{\mathrm{L,M,S}} P_x, \tag{4}$$

where coefficients c_x (Eq. (3)) determine how much each type of the cones participate in the brightness detection.

There still are two numbers for hue. First, one can notice that if there is only one type of receptor, it is possible to check whether the receptor was more or less stimulated. If there are two kinds of receptors, it is also possible to check their relative stimulations. Second, we assume that the brain is interested in emphasising small differences. Finally we define hue as

$$\boldsymbol{h} = \left(\ln\left(\frac{P_{\mathrm{L}}}{P_{\mathrm{M}}}\right),\ \ln\left(\frac{P_{\mathrm{S}}}{P_{\mathrm{M}}}\right) \right). \tag{5}$$

First of all one can notice that if $P_{\mathrm{L}} = P_{\mathrm{M}} = P_{\mathrm{S}}$, we do not have any information apart from brightness.

Following Wald's spectra [12] one can find for *monochromatic* stimulus

$P_R > 0$	$P_{\mathrm{S}}, P_{\mathrm{M}} \approx 0$	*red*
$P_{\mathrm{L}} > P_{\mathrm{M}}$	$P_{\mathrm{S}} \approx 0$	*orange*
$P_{\mathrm{L}} \approx P_{\mathrm{M}}$	$P_{\mathrm{S}} \approx 0$	*yellow*
$P_{\mathrm{L}} < P_{\mathrm{M}}$	$P_{\mathrm{S}} < P_{\mathrm{M}}$	*green*
$P_{\mathrm{L}} < P_{\mathrm{M}}$	$P_{\mathrm{S}} \approx P_{\mathrm{M}}$	*blue*
$P_{\mathrm{L}}, P_{\mathrm{M}} \approx 0$	$P_{\mathrm{S}} > 0$	*violet*

This explains why red-green or yellow-blue colours are impossible: sensing red needs $P_{\mathrm{L}} > P_{\mathrm{M}}$ whereas green needs $P_{\mathrm{L}} < P_{\mathrm{M}}$ (blue needs $P_{\mathrm{S}} > P_{\mathrm{M}}$ and yellow $P_{\mathrm{S}} < P_{\mathrm{M}}$). This definition generates opponent colour processes but the pairs of opponent colours: red-green and yellow-blue are not the principle, but the result of the way a human brain gets information.

Using this definition one may simulate a colour matching experiment. The experiment consists of mixing three monochromatic lights (red, green, and blue) to get the same colour sensation as for λ-monochromatic light. Although for some λs the condition takes the form: *blue + green = λ + red.*

To calculate colour matching functions three quantities have been computed for each λ: $r(\lambda)$, $g(\lambda)$, $b(\lambda)$ following this formula

$$r(\lambda)P_x(645) + g(\lambda)P_x(526) + b(\lambda)P_x(444)) = P_x(\lambda), \quad x = \mathrm{L, M, S}\,. \tag{6}$$

Numbers 645, 526, 444 nm have been chosen as wavelengths of red, green and blue light respectively. The results are shown in the Fig. 1. The obtained curves agree very well with experimental results.

The definition (5) is based only on three cones' stimulation functions and does not favour any hue but makes possible to simulate an experiment in which the chromatic response for a given hue was measured. The Jameson's and Hurvich's experiment [17] was aimed at two pairs of opponent hues: red-green and yellow-blue. The yellow (red) chromatic response was assumed to be proportional to the amount of blue (green) light which is necessary to cancel yellow (red) sensation. Details of the results of such an experiment depend on individual sensations of the observer, what was shown in the experiment.

To simulate the experiment we have set one condition for each curve: λ-light plus opposite-to-examined hue light should give neutral sensation. It is enough only for red chromatic response. For the right (left) red curve the amount of green light plus λ-light should give a yellow (blue) hue.

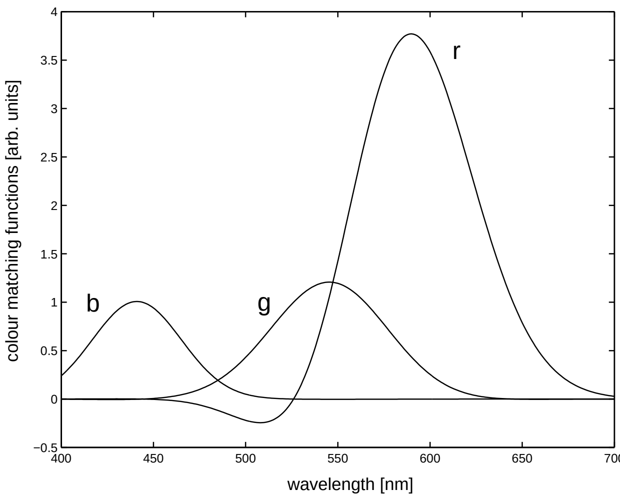

Fig. 1. Computed colour matching functions (see text for details). Values of parameters for P_xs have been obtained on the ground of the results of Wald's experiment [12].

For other curves we should take into account that in the experiment the observer could have seen different final hues in different part of the spectrum when particular chromatic response was measured. It is obvious that in such cases the hue changed smoothly from one to another.

Following the experiment we have chosen green as the final hue for the right part of the yellow curve and white for its left part. In case of green chromatic response function the hues were blue (right) and yellow (left part of the curve). For the blue curve as for the yellow one white and green were the hues but the former for the right end and the latter for the left end of the curve. In each case the condition has been put on the more changeable (in particular wavelength range) ratio of the definition (5).

The results are shown in the Fig. 2. In this modelling we are able to create only parts of the chromatic response functions, if we know or could guess the final hue. We can imagine that the appropriate partial curves should be connected to create the whole functions.

Another problem is the location of these curves related to the Y axis. The experiment was performed for chosen eye adaptation conditions. Adaptation of an eye needs extra modelling and is not included here.

The computed curves are similar to the experimental ones (in the cases for which enough experimental data are known), although the definition (5) generates hues after light detection (there is no colour before comparing cones' outputs) so it does not need anything like response of the visual system for a particular hue. In particular this "simulation" recreates the left branch of the red curve.

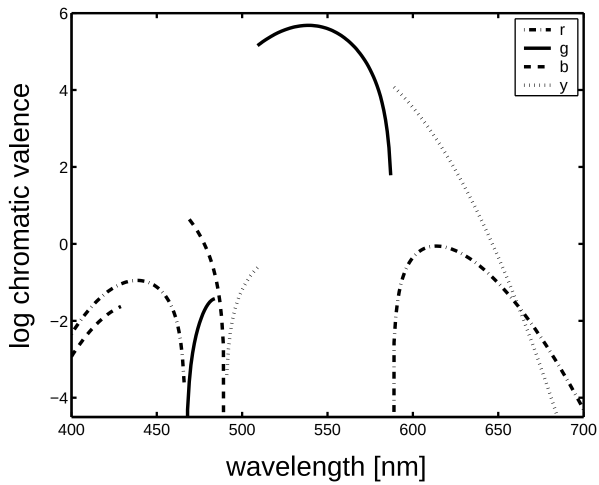

Fig. 2. Computed chromatic valences (*r-red, b-blue, g-green, y-yellow*); simulation of Jameson's and Hurvich's experiment [17]. Following the experiment 700, 588, 490, 467 nm was used as pure red, yellow, green and blue hues respectively. Values of parameters for P_xs have been obtained on the ground of the results of Wald's experiment [12]

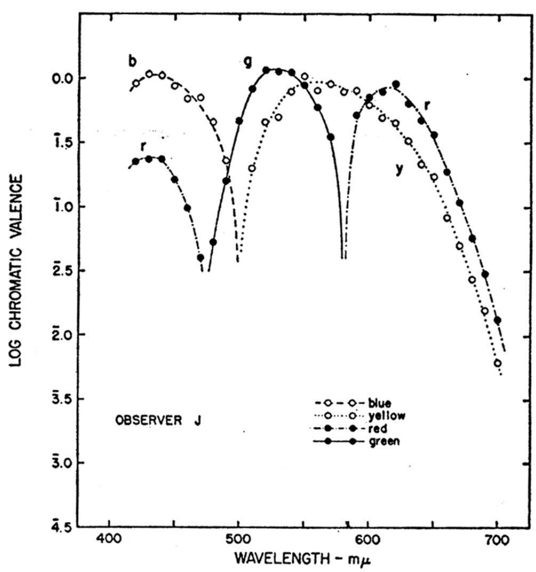

Fig. 3. Results of Jameson's and Hurvich's experiment on the chromatic response of the visual system for a given hue (red, green, yellow and blue). (comes from: D. Jameson, L.M. Hurvich *J. Opt. Soc. Am.* **45**, 546 (1955)).

5. Summary and discussion

One way to distinguish between objects with different $I(\lambda)$ is to compare intensity for all λs but we know that it is not the way Nature has chosen. There is no unique relation between $I(\lambda)$ and colour. Colour detection is located in the retina and is based on a few (three) types of photoreceptors. There is not any database in the retina to compare cones' outputs. Only relative comparison is possible. One can notice that if relation of cones' stimulation is meaningfully different (*e.g.* $P_{\rm L} > P_{\rm M}$ and $P_{\rm L} < P_{\rm M}$), our impression is meaningfully different too (red/orange and green/blue respectively). When both stimulations are comparable ($P_{\rm L} \approx P_{\rm M}$), new sensation appears: neither red nor green. If one changes wavelength continuously (starting from middle to long wavelengths), colour impression changes continuously as well, from green through yellow and orange into red. Where exactly pure yellow lies is a subjective impression [17] and depends on individual preferences.

Table I contains ranges of wavelengths for different colours. The data come from three different sources from the Internet [18–20] and can serve as an argument that colour impression is a really subjective sensation.

TABLE I

Ranges of wavelengths for different colours coming from different sources: 1 — [18], 2 — [19], 3 — [20].

Colour	Wavelength [nm]		
	1	2	3
red	630–770	630–780	620–700
orange	600–630	600–630	592–620
yellow	540–600	580–600	578–592
green	490–540	495–580	500–578
blue	440–490	440–495	446–500
violet	410–440	360–440	400–446

The definition in the form of the Eq. (5) is based on a few assumptions. First, mechanism of comparing of cones' outputs checks ratios of cones' stimulations. Second, the brain is interested to emphasise small differences. Neither of them should be controversial. All parameters have clear meaning and their values depend on individual features. The definition has not any extra parameters. What is the most important, the definition shows that special features of human colour vision (*e.g.* colour mixing) can be explained without assumption that any colour is favoured or that any special mechanism for detection of any particular colour exists, which is consistent with the fact that there is no colour outside our minds.

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