HUNGARIAN JOURNAL OF
INDUSTRY AND CHEMISTRY
Vol. 47(1) pp. 17–23 (2019)
hjic.mk.uni-pannon.hu
DOI: 10.33927/hjic-2019-04

SIMULATION OF COLOR AFTERIMAGES: AN APPROACH TO COMPUTING VIRTUAL COLOR PERCEPTION

LŐRINC GARAI *1 AND ANDRÁS HORVÁTH[2]

[1]Doctoral School of Multidisciplinary Engineering Sciences (MMTDI), Széchenyi István University, Egyetem tér 1, Győr, 9026, HUNGARY
[2]Department of Physics and Chemistry, Széchenyi István University, Egyetem tér 1., Győr, 9026, HUNGARY

Afterimages are a common and frequent perceptual phenomenon of everyday life. When looking into a high-intensity light source and suddenly turning away from it, a temporary "ghost" of the light source remains visible, for a while. The computer-graphics simulation of afterimages is based on biophysical and mathematical models as published in the literature. A subordinate of afterimages defined in our research is *virtual color perception,* that is in our interpretation an unusual and intense temporary color perception provoked by a rapid change in the color of the incident light. In research, the modelling of virtual color perception is a field that is by and large untouched. Our publication presents a kinetic model established to characterize the intensity and duration of virtual color perception as a function of rapid changes in the color of the incident light.

Keywords: afterimage, rod and cone photoreceptors, photopigment, kinetics

1. INTRODUCTION

In our vision, an afterimage is an illusionary image that appears after having been exposed to a prior one. Color afterimages are experienced in everyday life, for example, when driving at night the headlights of oncoming cars are so bright that when the driver looks away from them, the illusion of bright headlights still remains in perception [1]. When photorealistic images are rendered [1–4], some papers reported simulations of color afterimages by combining mathematical models [5–9].

A subordinate of afterimages defined in our research is *virtual color perception*, a phenomenon that originates from chromatic adaptation in photoreceptors influenced by environmental color interactions, and based on the sensitivity to light and adaptibility of each cone receptor.

The physiological background of virtual color perception in brief is as follows: human photopic (daylight) color vision is a combined response of type L (long wavelengths), M (medium wavelengths) and S (short wavelengths) cone receptors to adequate stimuli of light. The photopigment *rhodopsin* plays a key role in the process; the equilibrium of its relative concentration is achieved by the opposing processes of rapid cleavage when exposed to light and slow resynthesis in darkness [10, 11]. Adaptations of cone receptors to changes in the color of the incident light is time-consuming [12, 13], hence, a rapid change in the color of the incident light facilitates unusual and intense temporary color perception, the so-called *virtual color perception*. For example, when exposed to red light the sensitivity of L cone receptors is low and in this case is accompanied by the high sensitivity of M and S cone receptors. Following a rapid change in color from red to blue in the incident light, the sensitivity of S cone receptors remains temporarily high, resulting in perception of the color bright blue that transforms into common blue after a short period of time during which the relative concentration of photopigment is equilibrated (restored), i.e. this is the duration of *virtual color perception*.

The purpose of our work is to develop a computational kinetic model capable of simulating and quantifying virtual color perception.

In our research chromaticity diagrams are used. Note that changes in the xy coordinates [14] are not proportional to human color perception. To overcome this distortion, several chromaticity coordinates were defined, for example, CIE $u'v'$ [15].

The gamut of a device is the complete subset of colors it can produce. Usually, in an RGB (red, green, blue) device, it consists of a color triangle with two-dimensional chromaticity coordinates. A gamut is characteristic of the given display (screen) currently in use, for example, modern RGB LED displays are characterized by wider gamuts compared to old-fashioned cold cathode fluores-

*Correspondence: garailorinc@garailorinc.hu

Table 1: Gamut points

	CCFL		RGB LED	
Gamut point	x	y	x	y
B	0.2091	0.2218	0.1563	0.0307
B3R1	0.2753	0.2518	0.2837	0.1056
B2R2	0.3415	0.2817	0.4111	0.2181
B1R3	0.4077	0.3115	0.5385	0.3024
R	0.4739	0.3415	0.6658	0.3305
R3G1	0.4420	0.3837	0.5687	0.4236
R2G2	0.4101	0.4239	0.4717	0.5632
R1G3	0.3783	0.4652	0.3746	0.6679
G	0.3464	0.5064	0.2775	0.7028
G3B1	0.3121	0.4353	0.2472	0.5348
G2B2	0.2778	0.3641	0.2169	0.2827
G1B3	0.2434	0.2930	0.1866	0.0937

cent lamp (CCFL) displays that were frequently used about 10 years ago.

In our work, gamuts characteristic of CCFL and RGB LED desktop monitors were measured first. Following this, the simulation of virtual color perception obtained by gamut data as a result of a rapid change in the color of the incident light was conducted. Finally, preliminary validation tests were run on the aforementioned RGB LED desktop monitor in use [16].

2. Experimental

2.1 Measurement of the gamuts of the displays used in our experiments and key parameters of our model

The spectral power distribution of the red, green and blue primaries of two displays was measured by a spectroradiometer (a Flame Miniature Spectrometer by Ocean Optics, Inc. calibrated 12 strong lines of He, Ne, Ar and H_2 flashtubes). One of the displays used was that of an old notebook using a CCFL as a backlight and the other was a more modern one (HP ZR2440w) with a display using RGB LEDs as a backlight. Based on the spectral power distributions measured, the CIE 1931 (x, y) chromaticity coordinates were calculated for all three primaries of both displays, using a Color Matching Function (CMF) of 10° at a resolution of 1 nm between the wavelengths of 360 nm and 830 nm. Intermediate gamut point coordinates were calculated by interpolation. Gamut point numbers in Table 1 and Fig. 1 were further referred to as colors of incident light. In our kinetic model, actual color perception is compiled from the generally known mathematical relations [8, 9, 17] shown below.

The actual color perception J of a single (L, M or S) cone receptor can be calculated by the formula

$$J = DEp, \tag{1}$$

where D denotes a conversion constant between the cleavage of rhodopsin and neural impulses and here is

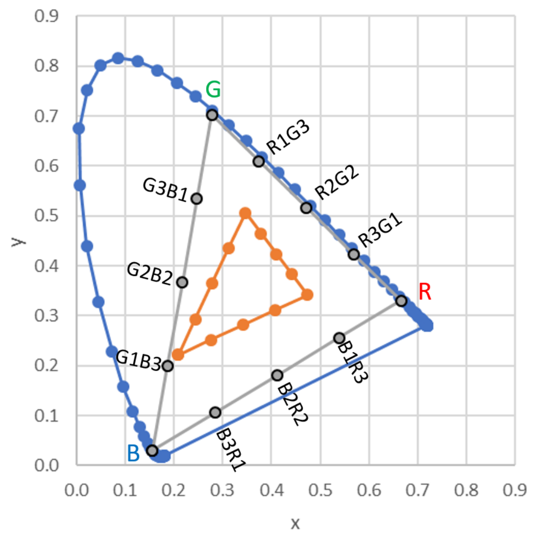

Figure 1: Chromaticity diagram of gamut points: an old CCFL display of a notebook (inner gamut) and an HP ZR2440w display (outer gamut)

equal to 1. The variable E represents the intensity of incident light expressed in trolands (Td). During the calculations a maximum luminance of the monitor of 300 cd/m^2 was used and a diameter of the pupil of 5 mm assumed. Therefore, the maximum retinal illuminance was equal to 5890 Td. The variable p denotes the relative concentration of photopigment (between 0 and 1).

The time differential of p determined from the rate of photopigment synthesis (Q_s), spontaneous photopigment cleavage (Q_c) and photoinduced cleavage (Q_i) is calculated by

$$\frac{\mathrm{d}p}{\mathrm{d}t} = Q_\mathrm{s} - Q_\mathrm{c} - Q_\mathrm{i}. \tag{2}$$

The variables of Eq. 2 are calculated by

$$Q_\mathrm{s} = \frac{1}{\tau}, \tag{3}$$

$$Q_\mathrm{c} = \frac{p}{\tau}, \tag{4}$$

and

$$Q_\mathrm{i} = \frac{E}{E_0}\frac{p}{\tau}, \tag{5}$$

where the time constant $\tau = 99$ 1/s and $E_0 = 20,000$ are used [13]. The following differential equation is composed from Eqs. 2–5:

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{1}{\tau} - \frac{p}{\tau} - \frac{E}{E_0}\frac{p}{\tau}. \tag{6}$$

The solution of Eq. 6 yields the actual relative concentration of photopigment:

$$p(t) = \frac{1}{b}\left[1 - (1 - p_0 b)\right] e^{-tb/\tau}, \tag{7}$$

where p_0 denotes the initial relative concentration of photopigment.

Finally, the equilibrium with regard to the relative concentration of photopigment p_e and percentage of photopigment cleaved b are related as follows:

$$p_e = \frac{1}{b} = \frac{E_0}{E + E_0}. \tag{8}$$

2.2 Simulation formula

In accordance with CIE 1931 [18, 19], the actual coordinates of color perception $x(t)$, $y(t)$ and $z(t)$ are calculated from the color coordinates of incident light x_i, y_i and z_i by equations Eqs. 9–24. In the equations below, variables indexed with L, M and S apply to cone receptors L, M and S, respectively.

$$E_L = E_{multip} \cdot M_{1,1\text{-}3} \times [x_i, y_i, z_i] \tag{9}$$

$$E_M = E_{multip} \cdot M_{2,1\text{-}3} \times [x_i, y_i, z_i] \tag{10}$$

$$E_S = E_{multip} \cdot M_{3,1\text{-}3} \times [x_i, y_i, z_i] \tag{11}$$

$$b_L = b_M = b_S = 1 + \frac{E_{multip}}{E_0} \tag{12}$$

E_{multip}, which is equal to $6,000$, denotes the light intensity of the display. The actual relative concentration of photopigment is calculated from the initial relative concentrations of photopigment p_{0L}, p_{0M} and p_{0S}:

$$p_L(t) = \frac{1}{b_L}(1 - (1 - p_{0L} b))e^{-tb/\tau} \tag{13}$$

$$p_M(t) = \frac{1}{b_M}(1 - (1 - p_{0M} b))e^{-tb/\tau} \tag{14}$$

$$p_S(t) = \frac{1}{b_S}(1 - (1 - p_{0S} b))e^{-tb/\tau} \tag{15}$$

For the purposes of iteration in simulations, the initial relative concentration of photopigment p_0 was equal to 0.1. From the actual relative concentrations of photopigment Eqs. 13–15, the color perception coordinates are as follows

$$J_L(t) = D \cdot p_L \cdot E_L, \tag{16}$$

$$J_M(t) = D \cdot p_M \cdot E_M, \tag{17}$$

$$J_S(t) = D \cdot p_S \cdot E_S, \tag{18}$$

where J_L, J_M and J_S denote the cone receptors of long, medium and short wavelengths, respectively.

To obtain more accurate color perception coordinates, tristimulus values were calculated:

$$X(t) = M^{-1}_{1,1\text{-}3} \times [J_L, J_M, J_S], \tag{19}$$

$$Y(t) = M^{-1}_{2,1\text{-}3} \times [J_L, J_M, J_S], \tag{20}$$

$$Z(t) = M^{-1}_{3,1\text{-}3} \times [J_L, J_M, J_S], \tag{21}$$

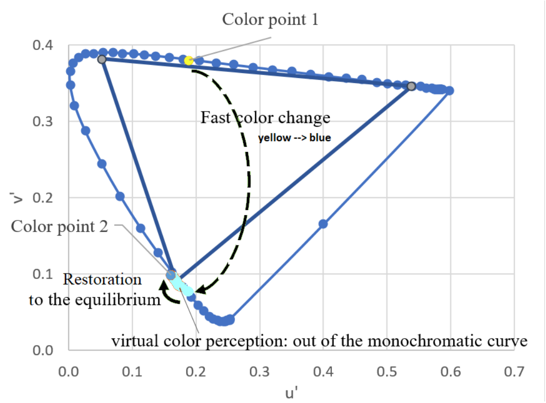

Figure 2: An example of fast color change leading to virtual color perception. Color point yellow shows primary color perception. Color points bright blue show virtual color perception as reflected by the tendency to reach equilibrium in photopigment relative concentration.

where M denotes a transformation matrix between tristimulus values X, Y and Z, and the actual color perception J. The actual color perception coordinates $x(t)$, $y(t)$, $z(t)$ are calculated by the following equations:

$$x(t) = \frac{X(t)}{X(t) + Y(t) + Z(t)}, \tag{22}$$

$$y(t) = \frac{Y(t)}{X(t) + Y(t) + Z(t)}, \tag{23}$$

$$z(t) = 1 - x(t) - y(t). \tag{24}$$

In accordance with the CIELUV (1976) chromaticity diagram, the actual color perception coordinates $x(t)$, $y(t)$ and $z(t)$ are transformed into coordinates $u'(t)$ and $v'(t)$ by an easy-to-compute method [19] :

$$u'(t) = \frac{4x(t)}{12y(t) - 2x(t) + 3}, \tag{25}$$

$$v'(t) = \frac{6y(t)}{12y(t) - 2x(t) + 3}. \tag{26}$$

The *intensity* of the actual virtual color perception is determined by

$$\Delta c = \sqrt{(u'(t) - u'_e)^2 + (v'(t) - v'_e)^2}, \tag{27}$$

where u'_e and v'_e denote color coordinates at equilibrium following restoration from virtual color perception (see *Restoration to the equilibrium* in Fig. 2).

A summary of variables and parameters is shown in Notations at the end of this paper.

2.3 Simulation

To understand the calculations, a graphical approach is shown in Fig. 2. Gamut color point 1 stands for the primary perception of the actual incident light, which is yellow here. With a rapid change in color from yellow to

Table 2: Example of iteration

$t(s)$	x_i	y_i	$u'(t)$	$v'(t)$	Δc
0.0	0.4250	0.56875	–	–	–
10.0	0.4250	0.56875	0.1893	0.3802	–
20.0	0.4250	0.56875	0.1892	0.3802	–
30.0	0.4250	0.56875	0.1891	0.3802	–
30.1	0.1400	0.05000	0.1748	0.0836	0.02075
30.2	0.1400	0.05000	0.1748	0.0837	0.02066
30.3	0.1400	0.05000	0.1747	0.0838	0.02057
30.4	0.1400	0.05000	0.1747	0.0838	0.02048
30.5	0.1400	0.05000	0.1746	0.0839	0.02039
30.6	0.1400	0.05000	0.1745	0.0840	0.02031
30.7	0.1400	0.05000	0.1745	0.0840	0.02022
30.8	0.1400	0.05000	0.1744	0.0841	0.02013
30.9	0.1400	0.05000	0.1744	0.0842	0.02004
31.0	0.1400	0.05000	0.1743	0.0842	0.01995
31.1	0.1400	0.05000	0.1743	0.0843	0.01987
31.2	0.1400	0.05000	0.1742	0.0844	0.01978
...	...	...	...	...	...
63.9	0.1400	0.05000	0.1611	0.0991	0.000126
64.0	0.1400	0.05000	0.1611	0.0991	0.000101
64.1	0.1400	0.05000	0.1611	0.0992	0.000092
64.2	0.1400	0.05000	0.1611	0.0992	0.000102

blue, a bright blue color appears in perception that transforms into common blue after a short period of time necessary for the restoration of the equilibrium in terms of the relative concentration of photopigment, which is the time period required for virtual color perception, namely for the perception of bright blue (Fig. 2).

Our kinetic simulation model (Section 2.2) is illustrated in Table 2. The first five lines in the first four columns show the same values of the color coordinates of incident light x_i, y_i, z_i, against time ($0 - 30$ seconds).

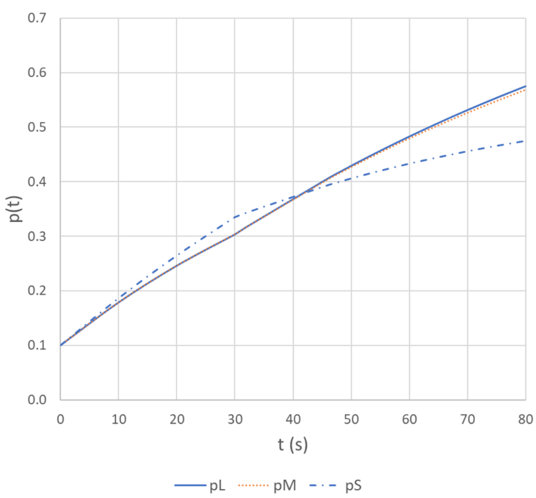

Figure 3: Photopigment relative concentration values in the iteration in Table 2

Over this 30 second-long period, the $u'(t)$ and $v'(t)$ values of color perception are quasi identical. However, after 30 seconds, a rapid change in color of the incident light from red to blue results in virtual color perception, as demonstrated by line 6 and column 5. The values of Δc in column 7 concern the intensity of virtual color perception. $(\Delta c)_{\max}$ denotes the peak intensity in virtual color perception and the minimum Δc stands for the duration of virtual color perception (t_{virtcol}). Actual relative concentrations of photopigment of cone receptors L, M and S are shown in the diagram in Fig. 3.

In terms of simulating virtual color perception, rapid changes in the color of incident light were indicated on CCFL and RGB LED monitors by the assignment of defined gamut points to each other (Fig. 1). Altogether, 24 changes in color were simulated.

2.4 Validation of the simulation

Our kinetic model was validated by a test that consisted of 20 subjects involving an in-house piece of software run in a Python environment. Accordingly, a homogeneous solid colored circle is displayed on a homogeneous background of a different color for 30 seconds (Fig. 4), then the circle disappears (Fig. 5) and the intensity and duration of virtual color perception is determined by the key inputs of the user. Further details concerning the test are found below:

- First, the test subject looked at a white screen for 30 seconds.

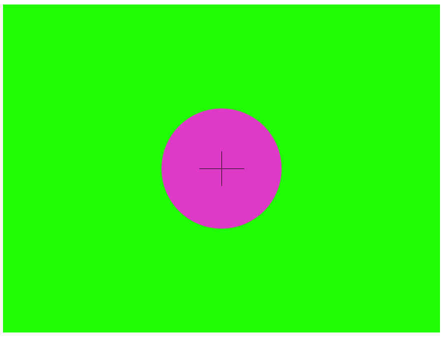

Figure 4: Second screen of validation test.

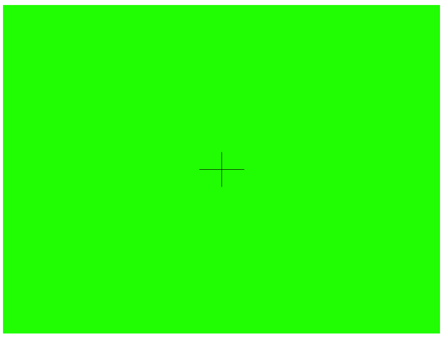

Figure 5: Third screen of validation test: circle removed.

Table 3: Comparison of virtual color perception intensity in model situations and in validation test results

Ranking in model		Ranking category	Ranking in validation test results		
ID	Rank		ID	Median of ranking	Corre-lation
R → G	1	High	B → G	1.00	No
G2B2 → R	2		B2R2 → G	2.00	Yes
G1B3 → R	3		R → G	3.00	Yes
B2R2 → G	4		B → R2G2	4.00	No
R → G2B2	5	Medium	R → G2B2	4.00	Yes
R2G2 → B	6	Low	G1B3 → R	4.50	No
G → B2R2	7		G2B2 → R	5.00	No
B → G	8		G → B2R2	5.00	Yes
B → R2G2	9		R2G2 → B	7.00	Yes

Matching percentage between model and validation test results: 56%

Table 4: Comparison of virtual color perception time period in model situations and in validation test results

Ranking in model		Ranking category	Ranking in validation test results		
ID	Rank		ID	Median of ranking	Corre-lation
R → G2B2	1	High	B → G	1.00	No
R → G	2		G1B3 → R	2.00	No
G → B2R2	3		B → R2G2	3.00	No
B2R2 → G	4		R → G2B2	4.00	Yes
R2G2 → B	5	Medium	G2B2 → R	4.00	No
G2B2 → R	6	Low	G → B2R2	4.50	No
B → R2G2	7		B2R2 → G	5.00	No
G1B3 → R	8		R → G	5.00	No
B → G	9		R2G2 → B	7.00	No

Matching percentage between model and validation test results: 11%

- Second, the eyes of the subject were fixed on a circle at the center of the subsequent colored image (Fig. 4) for 30 seconds. According to our definition, the color of the central circle represents the first gamut point, while the color of the background represents the second gamut point. Altogether, 9 assignments of gamut points have been validated so far.
- Third, the central circle suddenly disappeared (Fig. 5) and the subject responded according to the intensity and duration of virtual color perception experienced.
- The intensity of virtual color perception was rated on a four-grade scale, where zero stands for the absence of virtual color perception and 4 denotes its highest intensity. The duration of virtual color perception was indicated by the subject pressing a key as the perception faded away.

First, the assignments of gamut points for each test subject were ranked according to the intensity (Table 3) and duration (Table 4) of virtual color perception induced. Then, the median of the rank order with regard to the intensity and duration of virtual color perception was calculated.

Table 5: Intensity and time period of virtual color perception related to gamut points assignments

		$(\Delta c)_{\max}$		$t_{\mathrm{virtcol}}(s)$	
Color point 1	Color point 2	CCFL	RGB LED	CCFL	RGB LED
B	R3G1	0.00792	0.01212	30.9	24.5
B	R2G2	0.00553	0.00513	36.3	27.5
B	R1G3	0.00339	0.00197	41.9	16.0
R3G1	B	0.00794	0.01210	33.5	29.5
R2G2	B	0.00852	0.01367	34.9	32.2
R1G3	B	0.00953	0.01523	37.2	34.6
G3B1	R	0.00931	0.02381	27.1	29.3
G2B2	R	0.00958	0.02187	27.5	27.6
G1B3	R	0.00994	0.01989	28.1	25.8
R	G3B1	0.00920	0.02298	46.9	44.2
R	G2B2	0.00821	0.01686	51.2	52.8
R	G1B3	0.00735	0.01260	50.2	38.2
G	B3R1	0.00807	0.01789	48.2	41.1
G	B2R2	0.00648	0.01362	45.8	42.2
G	B1R3	0.00693	0.01722	30.5	31.0
B3R1	G	0.00324	0.01337	25.0	27.8
B2R2	G	0.00524	0.01799	33.7	33.7
B1R3	G	0.00749	0.02256	41.4	38.7
B	R	0.01036	0.01786	28.8	23.8
R	B	0.00788	0.01053	33.3	26.6
R	G	0.00980	0.02707	48.2	43.1
G	R	0.00915	0.02571	26.7	30.8
G	B	0.01084	0.01677	40.1	37.0
B	G	0.00234	0.00868	17.8	20.5

Since the number of test subjects was limited, the results could not be divided according to their age and gender. Further tests are needed to ensue virtual color perception with regard to gender and age.

3. Results and Discussion

In Table 5, the maximum $(\Delta c)_{\max}$ for the CCFL and RGB LED displays were identified during the rapid change in the color of incident light from gamut point G to B (from green to blue) and R to G (from red to green), respectively.

When compared to the CCFL display, the RGB LED display appears to yield higher $(\Delta c)_{\max}$ values with the exception of rapid changes in the color of the incident light from gamut point B to R2G2 (from blue to orange).

With regard to our results, the duration of virtual color perception seems to be platform-free, i.e. t_{virtcol} displayed on both the CCFL and RGB LED monitors was identical. However, rapid changes in the color of the incident light from gamut point B to R1G3 (from blue to yellowish green) was an exception with regard to the values of t_{virtcol}. As is shown in Table 5, t_{virtcol} computed on the CCFL display has doubled in value compared to that computed on the RGB LED display.

The kinetic simulation results so far point to the likelihood of the appearance of virtual color perception on all display platforms.

As for our preliminary tests performed on 20 test subjects so far as well as the parameters $(\Delta c)_{\max}$ and t_{virtcol}, a correlation between model situations (simulations) and the results of a validation test cannot be confirmed at present. Further tests, statistical evaluations and the introduction of additional parameters are also necessary to achieve more accurate conclusions.

4. Conclusion

Photopic human color vision is a combined response to the stimulation from light of red, green and blue cone receptors. Cone receptors adapt individually to the actual color of the incident light. Since the adaptation of cone receptors is time-consuming, virtual color perception can be achieved in the meantime by rapid changes in the color of the incident light.

Our kinetic model developed for individual cone receptors is based on mathematical correlations that simulate the intensity and duration of virtual color perception which result from rapid changes in color. According to our model, virtual color perception can result from both CCFL and RGB displays.

Our preliminary validations are yet to confirm a correlation between model situations (simulations) and the results of a validation test. Some refinements to the simulation by the introduction of additional parameters as well as further validation tests with regard to the gender and age of participants are indispensable to reach more accurate conclusions.

Acknowledgement

This research would not have been possible without the participation of volunteers from Széchenyi István University as test subjects.

Notations

Symbol	Meaning	Unit
J	in actual color perception: J_{L} = red cone receptors specific for long wavelength J_{M} = green cone receptors specific for medium wavelength J_{S} = blue cone receptors specific for short wavelength	dimensionless
p	relative photopigment concentration	dimensionless (range:0 . . . 1)
D	conversion constant between rhodopsin cleavage and neural impulses	dimensionless (value: 1)
E	incident light intensity	troland
Q_{s}	Synthesis of photopigment	dimensionless
Q_{c}	Spontaneous cleavage of photopigment	dimensionless
Q_{i}	Light induced cleavage of photopigment	dimensionless
τ	time constant in rhodopsin synthesis	seconds
p_0	photopigment initial relative concentration	dimensionless
$p(t)$	photopigment relative concentration at t time after p_0	dimensionless
b	percentage of photopigment cleaved	dimensionless
M	transformation matrix of tristimulus values XYZ and the actual color perception J	dimensionless

REFERENCES

[1] Mikamo, M.; Slomp, M.; Raytchev, B.; Tamaki, T.; Kaneda, K.: Perceptually inspired afterimage synthesis, *Computers & Graphics,* 2013 **37**(4), 247–255 DOI: 10.1016/j.cag.2013.02.008

[2] Gutierrez, D.; Anson, O.; Munoz, A.; Seron, F. J.: Perception-based rendering: eyes wide bleached in Dingliana, J.; Ganovelli, F. (eds): Eurographics 2005 - Short Presentations (The Eurographics Association, Geneve, Switzerland) 2005 pp. 49–52 DOI: 10.2312/egs.20051021

[3] Ritschel, T.; Eisemann, E.: A computational model of afterimages, *Comput. Graph. Forum,* 2012 **31**(2pt3), 529–534 DOI: 10.1111/j.1467-8659.2012.03053.x

[4] Horváth, A; Dömötör, G.: Computational simulation of mesopic vision based on camera recordings, *Light and Engineering,* 2014 **22**(1), 61–67

[5] Reidenbach, H.-D.: Determination of the time dependence of colored afterimages in Stuck, B. E.; Belkin, M.; Manns, F.; Söderberg, P. G.; Ho, A. (eds): Proceedings Ophthalmic Technologies XVIII **6844**, 2008 DOI: 10.1117/12.762852

[6] Padgham, C. A.: Quantitative study of visual afterimages, *Brit. J. Ophthal.,* 1953 **37**, 165–170 DOI: 10.1136/bjo.37.3.165

[7] Padgham, C. A.: Measurements of the colour sequences in positive visual after-images, *Vision Res.,* 1968 **8**(7), 939–949 DOI: 10.1016/0042-6989(68)90142-9

[8] Alpern, M.: Rhodopsin kinetics in the human eye, *J. Physiol.,* 1971 **217**(2), 447–471 DOI: 10.1113/jphysiol.1971.sp009580

[9] Smith, C. V.; Pokorny, J.; Van Norren D.: Densitometric measurement of human cone photopigment kinetics, *Vision Res.,* 1983 **23**(5), 517–524 DOI: 10.1016/0042-6989(83)90126-8

[10] Linksz, A.: An essay on color vision and clinical color-vision tests, *Am. J. Ophthalmol.,* 1964 **58**(3), 513 DOI: 10.1016/0002-9394(64)91250-4

[11] Hurvich, L. M.: Color Vision, (Sinauer Associates Inc., Sunderland, USA), 1981 ISBN: 978-0878933365

[12] Ábrahám, Gy.; Kovács, G.; Antal, Á.; Németh, Z.; Veres, Á. L.: Jármű optika (in Hungarian), 2014 `http://www.mogi.bme.hu/TAMOP/jamu_optika/ch02.html#ch-II.3.3.2.2` (downloaded on: 02/10/2018)

[13] Szentágothai J.: Functionalis anatomia, (in Hungarian) (Medicina Kiadó, Budapest, Hungary), 1977, vol. 3, pp. 1590–1597

[14] Colorimetry, 3rd Edition, CIE 15:2018 ISBN: 978 3 901906 33 6

[15] `http://www.color-theory-phenomena.nl/10.03.htm` (downloaded on: 02/10/2018)

[16] Csuti P.: The characterization of the photometry and colorimetry of light emitting diodes, PhD dissertation (in Hungarian) DOI: 10.18136/PE.2016.642 (http://konyvtar.uni-pannon.hu/doktori/2016/Csuti_Peter_dissertation.pdf)

[17] Horváth A.: A fényterjedés és -észlelés fizikája mérnököknek (in Hungarian), (SZE-MTK, Fizika és Kémia Tanszék, Győr) 2013, pp. 165-178, ISBN: 978-963-7175-97-8

[18] Smith T.; Guild J.: The C.I.E. colorimetric standards and their use, *Trans. Opt. Soc.*, 1932 **33**(3), 73–134 DOI: 10.1088/1475-4878/33/3/301

[19] Schanda J.: Colorimetry: understanding the CIE system (John Wiley & Sons, Inc., New Jersey, USA), 2007 DOI: 10.1002/9780470175637