

Paper

Towards a New Colour Appearance Model for Self-luminous Stimuli

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ABSTRACT

Based on the experimental visual data obtained for self-luminous stimuli surrounded by a dark background, a new colour appearance model (CAM) for unrelated self-luminous stimuli, CAM15u, was previously developed. To extend the model to related self-luminous stimuli, the colour appearance of coloured self-luminous stimuli surrounded by a luminous background was evaluated using the magnitude estimation method. Experiments have been performed in Belgium and in Argentina using two different experimental setups. With a LED setup in the Belgian laboratory, visual data on the perception of brightness, hue and amount of white of 30 coloured self-luminous stimuli surrounded by a luminous background were collected. Luminance levels of the stimuli and the background were respectively 50cd/m^2 and 28cd/m^2 (positive contrast condition). With a projector setup in the Argentinian laboratory, visual data on the perception of brightness and amount of white of 32 coloured self-luminous stimuli surrounded by a luminous background were collected. Luminance levels of the stimuli and the background were respectively 10cd/m^2 and 5.6cd/m^2 (positive contrast condition). For both experiments; the brightness scaling shows a clear and prominent Helmholtz–Kohlrausch effect. This effect describes the impact of the saturation of a stimulus on the perceived brightness and has been seriously underestimated in earlier CAMs. Both brightness, hue and amount of white are found to be well predicted by CAM15u, for this positive contrast condition.

KEYWORDS: colour appearance model, self-luminous stimuli

1. Introduction

The fundamental goal of colour appearance research is to look for correlates between the measured optical spectral data of a stimulus and its corresponding perceptual attributes such as Brightness Q (bright and dim), Hue quadrature H (expressed as perceived combinations of red, yellow, green and blue) and Colourfulness M (vivid and dull). From a physical point of view, any colour stimulus can be described by its spectral radiance from which the tristimulus values (X, Y, Z) or the cone fundamental responses (L, M, S) can be calculated. In order to integrate adaptation and contrast effects, the background must be characterized too.

Related colours are colours perceived to belong to areas seen in relation to other colours¹⁾. A typical example is the colour of an object which is seen in relation to the illuminant (white) and to the background surrounding the object.

Pure unrelated colours are colours that are perceived to belong to areas seen in isolation from any other co-

lours^{1,2)}. A self-luminous stimulus surrounded by a dark background, like a traffic or marine signal light viewed during a dark night, is a typical example of an unrelated colour.

Self-luminous stimuli such as light sources surrounded by a rather bright background define a subcategory of related colours. However, the self-luminous stimulus and the background stimulus are uncorrelated, contrary to reflective related stimuli in which both the colour of the stimulus and surround are correlated due to a common illumination. The spectra of the stimulus and the surround can be changed independently. As with any related colour, the perception of the stimulus is influenced by the luminance and colour of the environment through processes such as chromatic adaptation, simultaneous contrast, etc.

Colour appearance models (CAM) use the spectral radiance of the stimulus and background as input and generate absolute values for the visual correlates³⁾. In these models, many of the physiological processes

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taking place in the eye, retina and brain (such as cone saturation and adaptation) are approximately simulated. Stimulus size, location within the field of view, background and surround are also important parameters influencing the visual perception.

Various colour appearance models dealing with related colours have been developed. One of them, CIECAM02⁴⁾ is recommended by the "Commission Internationale d'Eclairage (CIE)". In CIECAM02, the latest developments regarding chromatic adaptation, luminance adaptation, cone saturation and noise, influence of background and surround are implemented.

For pure unrelated colours which have a dark background adapting field, Hunt²⁾ developed CAM97u in 1998. However, recent experiments have illustrated its poor performance. In contrast to the CAM for related colours, which was reviewed with CIECAM02⁴⁾, only Fu et al.⁵⁾ and Withouck et al.⁶⁾ proposed some small changes to CAM97u. Based on the data of an extensive magnitude estimation experiment, a new colour appearance model for unrelated self-luminous stimuli, CAM15u, has been designed by Withouck et al.⁷⁾. The main features of the model are the use of the absolute spectral radiance of the stimulus as input, the use of the CIE 2006 cone fundamentals⁸⁾, the inclusion of the Helmholtz-Kohlrausch effect, the "amount-of-neutral" as an alternative perceptual attribute to saturation and a simplified calculation procedure compared to existing models. The model predicts the brightness, hue, colourfulness, saturation and the amount-of-neutral of unrelated stimuli. The CAM15u model is restricted to photopic, non-glary unrelated stimuli with a field of view of 10°.

For the evaluation of self-luminous stimuli surrounded by a luminous uncorrelated background, there is at present no agreed model. Nevertheless, this situation frequently occurs in everyday situations and the modelling of these kind of stimuli becomes very important when dealing with issues such as the brightness and glare perception of, light sources, smartphones and advertisement billboards. Especially the glare of LED-

based fixtures, exhibiting very high luminance must be considered. In the long term, this model will allow for a better evaluation of the quality of lighting in terms of glare, contrast and harmony and will provide an interesting instrument to describe the visual experience of the total lit environment.

Extending the CAM15u model to a complete CAM for related self-luminous stimuli requires the study of the impact of a self-luminous background on stimulus appearance. As a first step the applicability of CAM15u for related stimuli in a positive contrast condition was investigated. To minimize confounding factors, this study was limited to positive contrast stimuli as CAM15u was designed for such stimuli with respect to a black background. In this paper the CAM15u model for unrelated stimuli and the experiments and visual data underpinning the model are summarized. Next, new experiments on the perception of brightness, hue and amount-of-neutral of self-luminous stimuli seen in positive luminance contrast against a self-luminous background (related stimuli) are presented. Finally, the predictive performance of the CAM15u model, as well as several other CAMs from literature for unrelated stimuli was analyzed.

2. Methodology

2.1 Methodology

In the center of a wall in a darkened viewing room of 3m wide by 5m long by 3.5m high, a circular stimulus with a field of view (FOV) of 10° was created to generate the (unrelated) self-luminous stimuli for the experiments (Figure 1). The stimulus is produced by a number of red, green, blue and white light-emitting diodes (LEDs) mounted inside a white cylindrical cavity covered with a diffuser. A test set of 105 stimuli was carefully selected (see Figure 2). These stimuli, spectrally measured using a calibrated telespectroradiometer, were chosen to cover a large area of the chromaticity diagram. Their luminance values (calculated using the CIE 1964 10° color matching functions (CMF)) were ran-

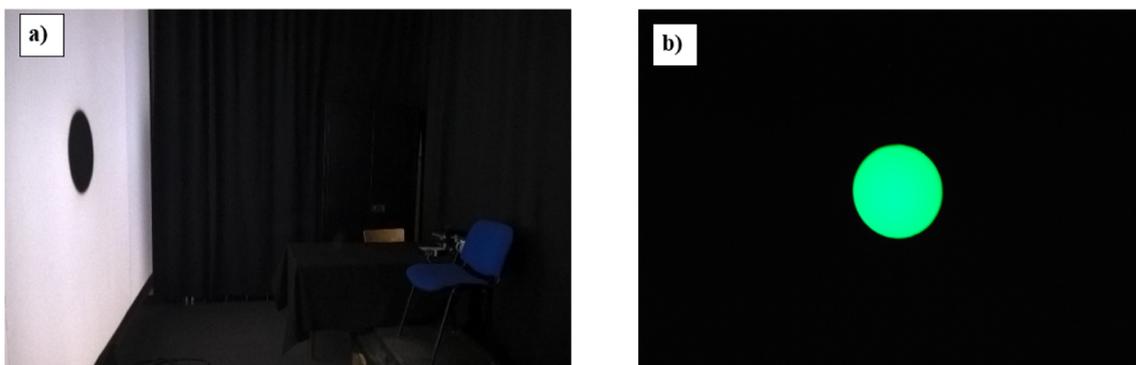


Figure 1 a) Viewing room with dark circular stimulus and luminous background, b) self-luminous stimulus with dark background from the observer's point of view.

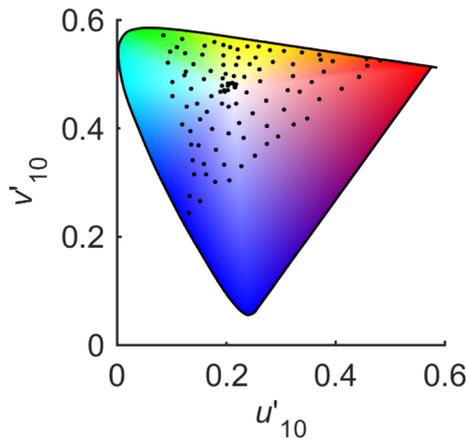


Figure 2 CIE 1976 u'_{10} , v'_{10} chromaticity coordinates of the 105 test stimuli.

domly selected from a 6 to 60 cd/m² luminance range, which provides photopic viewing conditions while avoiding glare in a dark environment.

In the experiment, the brightness, hue and “amount-of-white” perception of unrelated self-luminous stimuli was investigated using the magnitude estimation method. The “amount-of-white”, which was later called “amount-of-neutral”, has been proposed as a new attribute, and basically corresponds to a layperson’s conception of existing attributes such as colourfulness, chroma or saturation. It was introduced based on the results of a preliminary pilot study revealing that laypersons often have difficulty understanding, and hence judging, the colourfulness of a stimulus. When scaling the amount of neutral, observers were asked to assign a percentage of white/neutral versus the coloured contribution perceived in each stimulus. For hue, observers needed to identify the unique hues (red, green, yellow, blue) they could recognize in the stimulus, as well as their relative proportions: e.g., 60% red and 40% yellow for a particular orange stimulus. When scaling brightness, the stimuli were rated in comparison with a 51 cd/m² reference achromatic stimulus shown in temporal juxtaposition and to which a brightness value of 50 was attributed. The luminance of the reference achromatic stimulus was chosen to correspond to a perceived brightness (as calculated by the CAM97um model⁶) approximately midway the brightness range of all the stimuli in this experiment. The chromaticity of the reference stimulus (u'_{10} , v'_{10} =0.2111, 0.4750) was close to that of the equi-energy stimulus, SE (u'_{10} , v'_{10} =0.2105, 0.4737); ΔE_{uv} =0.0014. Twenty observers, 9 female and 11 male, with ages ranging between 21 and 32 years (average 24.5) participated in the psychophysical experiment. All had normal colour vision according to the Ishihara 24 plate Test for Colour Blindness and the Farnsworth-Munsell 100 Hue Test.

2.2 The model

Inspired by other CAMs such as CAM97u²) and CAMFu⁵), a new model to predict the colour appearance of unrelated self-luminous colours, CAM15u, has been developed⁷). In what follows, the basics of the CAM15u model are summarized.

In the CAM15u model, the new set of cone fundamentals provided by CIE are used to calculate the fundamental cone excitations, ρ_{10} , γ_{10} , β_{10} , of the stimulus:

$$\begin{aligned}\rho_{10} &= 666.7 \int_{390}^{830} L_{e,\lambda}(\lambda) \bar{l}_{10}(\lambda) d\lambda \\ \gamma_{10} &= 782.3 \int_{390}^{830} L_{e,\lambda}(\lambda) \bar{m}_{10}(\lambda) d\lambda \\ \beta_{10} &= 1444.6 \int_{390}^{830} L_{e,\lambda}(\lambda) \bar{s}_{10}(\lambda) d\lambda\end{aligned}\quad (1)$$

With $L_{e,\lambda}(\lambda)$ the spectral radiance of the stimulus and $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ the CIE 2006 10° cone fundamentals in terms of energy⁹). The coefficients were chosen such that for an equi-energy spectrum all three cone excitations are equal to the numerical value of the CIE 1964 10° luminance. Because of the restrictions of the model, i.e., photopic stimuli without glare, the compressed cone responses ρ_c , γ_c and β_c can be calculated from the cone excitations ρ_{10} , γ_{10} , β_{10} using a cubic power law:

$$\begin{aligned}\rho_c &= \rho_{10}^{1/3} \\ \gamma_c &= \gamma_{10}^{1/3} \\ \beta_c &= \beta_{10}^{1/3}\end{aligned}\quad (2)$$

By minimizing the mean of the squared residual errors between the observed brightness perception of 15 achromatic stimuli and the prediction of the achromatic signal (see below), the optimal value for the power occurring in Eq. (2) was found to be 0.332, which has been changed into 1/3. Such a cube root function has often been used to relate physical quantities of the stimulus to visual sensation¹⁰).

Next, a transformation of the compressed responses into three neural signals is performed: the achromatic signal A , and two colour difference signals a and b , respectively related to redness-greenness and yellowness-blueness perception. The achromatic signal is composed of a weighted sum of the three cone responses. The weights were taken in accordance with the estimated numerical distribution of the cones in the retina $\rho:\gamma:\beta$ of about 40:20:1²). These weighting coefficients are exactly the same as the ones used in CIECAM02¹¹).

$$A = c_A \left(2\rho_c + \gamma_c + \frac{1}{20} \beta_c \right) \quad (3)$$

The value of the free parameter c_A (Eq. (3)) was set to

3.22 by anchoring the achromatic signal A of this model to the achromatic signal of CAM97u using the same 15 achromatic stimuli.

The colour difference signals a and b are taken to be the same as proposed by Hunt¹²⁾:

$$a = c_a \left(\rho_c - \frac{12}{11} \gamma_c + \frac{\beta_c}{11} \right) \quad (4)$$

$$b = c_b (\rho_c + \gamma_c - 2\beta_c) \quad (5)$$

c_a and c_b are constants which were determined by fitting the experimental data (see below).

It is believed that the ratio of the colour difference signals a and b causes a hue sensation in our visual cortex²⁾. By taking the inverse tangent of a and b , the hue angle h can be calculated:

$$h = \frac{180}{\pi} \tan^{-1}(b/a) \quad (6)$$

To express hue in terms of a quadrature scale, the hue angle h is linearly transformed from a 0° – 360° range to a 0–400 range:

$$H = H_i + 100 \frac{h' - h_i}{h_{i+1} - h_i} \quad (7)$$

With h_i the unique hue angle obtained from Fu et al.⁵⁾, H_i the unique hue quadrature, $h' = h + 360$ if h is less than h_i , otherwise $h' = h$, and a value of i chosen so that h' is equal to or greater than h_i and less than h_{i+1} . The parameters c_a and c_b are determined by minimizing the mean of the squared residual errors between the experimentally observed hue quadrature and the predicted hue quadrature using Eq. (7): $c_a = 1$ and $c_b = 0.117$.

The colourfulness, defined as the perception according to which the perceived colour of an stimulus appears to be more or less chromatic, can be represented by the strength of the colour difference signals a and b ¹³⁾:

$$M = 135.5 \sqrt{a^2 + b^2} \quad (8)$$

The numerical parameter was found by anchoring the colourfulness M of the CAM15u model to the colourfulness scale used in CAM97u.

A first estimate of the perceived brightness, is given by the achromatic signal A of Eq. (3)¹³⁾. However, brightness perception is also influenced by the strength of the colour of the stimulus (cfr. Helmholtz–Kohlrausch effect):

$$Q = A + c_{HK1} \times M^{c_{HK2}} \quad (9)$$

The parameters c_{HK1} and c_{HK2} were determined by minimizing the mean of the squared residual errors between the experimentally observed and the predicted brightness of the test set. c_{HK1} was found to be equal to 2.559 and c_{HK2} to 0.561. In Figure 3, the observed bright-

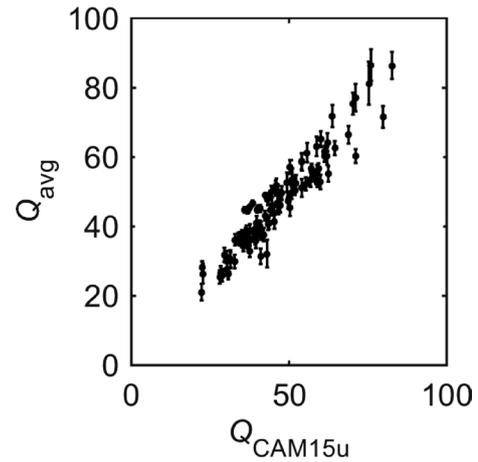


Figure 3 Average observed brightness, Q_{avg} , with standard error bars against the brightness prediction, Q_{CAM15u} .

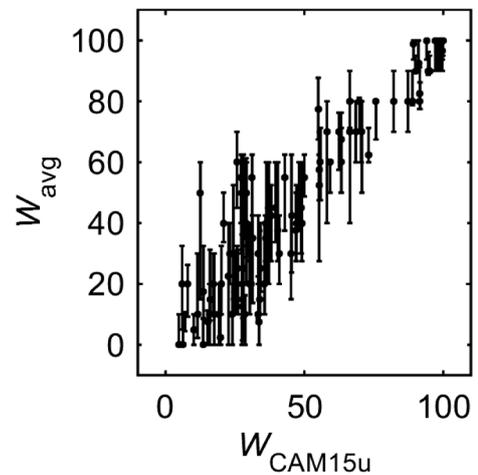


Figure 4 Average observed amount-of-neutral, W_{avg} , with interquartile range bars against the predicted amount of white, W_{CAM15u} .

ness is plotted against its CAM15u prediction.

Saturation can be defined as the colourfulness M relative to the brightness Q :

$$s = \frac{M}{Q} \quad (10)$$

Finally, the function predicting the amount-of-neutral was determined by minimizing the mean of the squared residual errors between the experimentally observed amount-of-neutral and a sigmoidal function of the saturation:

$$W = \frac{100}{1 + 2.29 \times s^{2.68}} \quad (11)$$

In Figure 4, the observed amount-of-neutral is plotted against its CAM15u prediction.

An additional magnitude estimation experiment was carried out to validate the CAM15u model and several other models published in literature. It was found that,

despite its simplicity, CAM15u performs better or at least equally well compared to the existing CAMs. For more information about CAM15u, the reader is referred to the recent literature⁷.

3. Towards a new CAM for self-luminous stimuli

3.1 Methodology

3.1.1 Experiment setup

As a first step towards extending the CAM15u model, a series of experiments have been performed to investigate the impact of the introduction of a self-luminous background on the colour appearance of self-luminous stimuli, specifically on the perceived brightness. Experiments have been performed in Belgium and in Argentina using two different experimental setups.

In a first one, located in the Belgian laboratory, the stimuli have been generated using LEDs in a setup as described by Withouck et al.⁷. Both the background and the stimulus were optically characterized using a telescopic measuring head coupled to a spectroradiometer (QE65Pro by Ocean Optics). The luminance uniformity of the stimulus area and of the wall were checked using an imaging colorimeter (MURATest by Eldim). The uniformity of the wall and the stimulus are within 10% of the mean.

Thirty test stimuli, divided in 6 different hues series, were selected. For each hue, 5 different stimuli with increasing saturation have been chosen. The CIE 1976 u'_{10} , v'_{10} chromaticity coordinates of the 30 stimuli, as determined from spectral measurements, are illustrated in Figure 5a. The luminance level of all 30 stimuli was fixed at 50.0 cd/m^2 (standard deviation 0.9 cd/m^2).

For comparison purposes with previous results and to minimize confounding factors, only positive luminance contrasts to the background were used at this stage. The luminance of the background, with a correlated colour temperature (CCT) of 3880K, was set at its lowest achievable level (28 cd/m^2). Luminance values were calculated using the standard spectral luminous

efficiency function $V_{10}(\lambda)$ for the CIE 10° observer¹⁴.

A second, Argentinian, experimental setup was composed of a self-luminous wall generated using a large diffusing screen illuminated from the rear by a projector. Using a projector a variety of stimuli and surroundings, with variable shape, size, color and luminance are easily generated. The observations are made from the front side, and the head of the participant was fixed using an ophthalmologic support. Analogous to the experiments described in Withouck et al.⁷, the total field of vision of the self-luminous display exceeds 40° in order to fill the human visual field. In the center of this screen a circular stimulus with a 10° FOV is projected. Both the background and the stimulus were optically characterized using a spectroradiometer (Photo Research PR-715 SpectraScan). This spectroradiometer was also used to check the luminance uniformity of the stimulus area and wall, both of which were within 10% of their mean values.

Thirty two stimuli with a fixed luminance of 10 cd/m^2 were selected at 8 different hues. For each hue, 4 different stimuli with increasing saturation have been chosen (Figure 5b). To maintain the same luminance ratio as the one used in the LED setup, the background luminance was taken as 5.6 cd/m^2 with a CCT of 5534K. Again, all the stimuli have a positive contrast to the background.

3.1.2 Stimulus evaluation

Evaluation of brightness

Brightness is one of the absolute attributes of the visual sensation according to which an area appears to emit more or less light. Visual data on the brightness perception of the test stimuli were obtained in a magnitude estimation experiment in which a group of observers were asked to rate, on a half-open scale, the brightness of the test stimulus in comparison to that of a reference stimulus. The results of this method are numerical and scalable data for the observed brightness^{4, 15, 16}. Immediately after the experiment, the observers were asked to

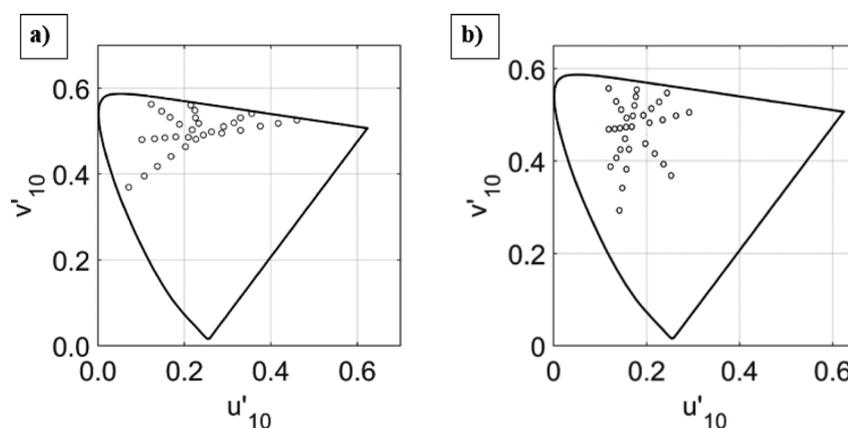


Figure 5 CIE 1976 u'_{10} , v'_{10} chromaticity coordinates of the 30 test stimuli generated using the LED setup (a) and the 32 stimuli generated using the projector setup (b).

answer a series of questions about their comfort in the room and about the brightness evaluation method.

Presenting an explicit reference stimulus

In a first series of experiments a reference stimulus was explicitly shown for 15s prior to every test stimulus. The reference stimulus had the same chromaticity coordinates and luminance level as the background (LED based setup: $u'_{10}=0.235$ $v'_{10}=0.490$ and $L=28\text{cd/m}^2$, projector based setup: $u'_{10}=0.211$, $v'_{10}=0.472$ and $L=5.6\text{cd/m}^2$). To this reference, a fixed brightness value of 100 was attributed for the LED based setup and 25 for the projector based setup. The test stimulus is then presented for 15s and the observers had to make an estimation of the stimulus brightness relative to that of the reference.

Using the background as a reference

In a second experiment, the background itself served as the reference stimulus for the brightness evaluation. In this case, the reference was presented simultaneously with the test stimulus. Again, a fixed brightness value of 100 was attributed to the reference. The test stimuli were again presented for 15s and the observers had to rate the brightness relative to the background. This experiment was only performed using the LED setup.

Evaluation of hue and amount of neutral

The evaluation method for hue and amount-of-neutral has been slightly changed compared to the experiments on which CAM15u was based and a more graphical approach has been selected. In Figure 6, an example of the response sheet of an observer is shown. For every stimulus the observers had to put a cross in these two columns and on the circumference of the circle. The first column, "light versus dark", (*licht* and *donker* in Dutch), was used for evaluating the lightness of the stimuli. Observers were free to use their own interpretation. The second column, "colourfull versus neutral" (*kleurrijk* and *neutraal* in Dutch) was used for the assessment of the amount-of-neutral. Observers had to record the hue of the stimulus by putting a cross on

the circumference of the circle (*rood*=red; *geel*=yellow; *groen*=green and *blauw*=blue). The change in assessment procedure was done as observers found it easier to intuitively put a mark than responding to the interrogator's questions with numerical values¹⁷. For 17 of the 22 Belgian observers, the lightness (*licht* versus *donker*) was the most difficult question. For 15 of the 22 Belgian observers, evaluating the hue by putting a cross on the circumference was the easiest task.

In the Argentinean laboratory, hue was not measured. For amount-of neutral, the same evaluation method as that used in the development of CAM15u was used.

3.1.3 Observers

The Belgian test panel was composed of 22 observers with normal colour vision, tested by the Ishihara 24 plate test, with ages ranging from 20 to 50 years (average age was 30 years and the median was 27 years old) and with an approximately 50-50 male-to-female ratio (12 males and 10 females). The Argentinian observer panel was composed of 20 observers (10 male, 10 female) aged between 26 and 36 years (average age was 29.5 years).

3.2 Results

3.2.1 Observer variability

The coefficient of variation can be used to analyze the goodness of a fit between two sets of data. If these two sets have a perfect agreement, the coefficient of variation will be zero. The results of the individual observers will be converted to an 'average observer' by calculating the geometric mean. Inter-observer variability will be evaluated by calculating the Coefficient of Variation (CV) between the individual and the average observer¹⁸:

$$CV=100\sqrt{\frac{1}{n}\sum_{i=1}^n\frac{(A_i-fB_i)^2}{A^2}} \text{ with } f=\frac{\sum_{i=1}^n A_i B_i}{\sum_{i=1}^n B_i^2} \quad (12)$$

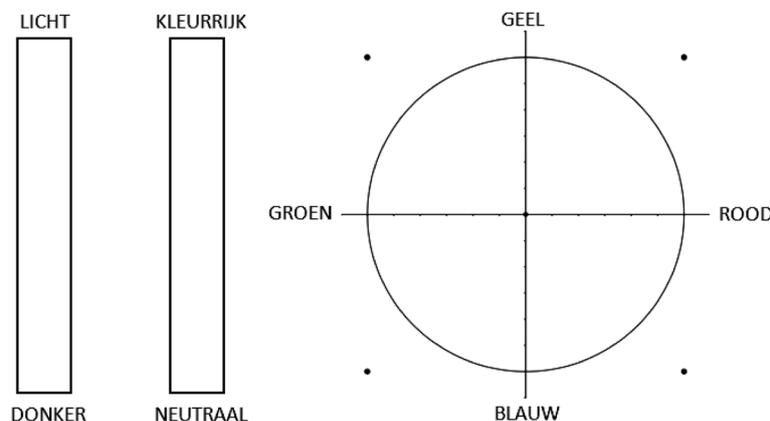


Figure 6 Graphical response sheet.

In this equation, B_i represents the perceptual attribute (brightness, hue quadrature or amount of white) of stimulus i of the individual observer. A_i represents the geometric mean of the brightness and arithmetic mean of hue quadrature or amount of white of all observers. \bar{A} represents the arithmetic mean of A_i for all n stimuli. The intra-observer variability, a measure for how consistent an observer is with himself, can be assessed using the same metric. Intra-observer variability was assessed using the data of 15 repeated stimuli. The data obtained for the Belgian observers are gathered in Table 1.

The CV values for the inter-observer agreement for the brightness evaluation ranged from 16 to 36 with an average of 24 if the background is used as a reference, and 22 if a reference stimulus is presented in temporal juxtaposition. These inter-observer CV values are consistent with previous studies^{19, 20}.

However, when analyzing only the data of the male observers, a mean intra-observer CV of 16 (standard deviation, $s=7$) was found when the background was used as reference and a value of 22 ($s=7$) was found when a reference stimulus was presented before the actual

stimulus. A Kolmogorov-Smirnov test and a Shapiro-Wilk confirmed that the male intra-CV's are Gaussian distributed. After performing a paired sample t -test on both male distributions (with successive reference stimulus and with simultaneous reference background), the difference turned out to be significant ($p=0.00012$). In the questionnaire directly following the experiment, 10 out of the 12 males responded that the brightness estimation with respect to the background reference was much easier. They all responded that whenever the stimulus and the reference were present at the same time, a more precise estimation could be made. The inter- and intra-observer CV values for the Argentinian observers were respectively 25 and 15, all in line with the Belgian experiments and with values mentioned in literature⁷.

3.2.2 Brightness perception

The geometric mean of the brightness perception (evaluated using reference stimulus) as a function of the saturation level is shown in Figure 7. It is clear that in both the Belgian and Argentinian studies (each performed with a different luminance level) the perceived brightness increases with increasing saturation for each

Table 1 Observer variability in terms of CV for the Belgian observers.

Observer	Gender	Brightness				Hue quadrature		Amount of neutral	
		Background reference		Reference stimulus		CV-intra	CV-inter	CV-intra	CV-inter
		CV-intra	CV-inter	CV-intra	CV-inter	CV-intra	CV-inter	CV-intra	CV-inter
1	m	8	20	19	25	19	17	24	20
2	m	8	25	12	20	13	9	19	18
3	m	20	27	29	25	15	12	25	16
4	m	24	27	29	17	17	20	28	27
5	f	17	31	18	25	14	16	27	22
6	m	13	18	22	16	9	15	19	17
7	m	9	16	15	17	12	10	24	28
8	m	9	23	10	19	16	18	26	29
9	f	16	28	28	29	8	14	20	14
10	m	15	25	22	23	21	17	21	27
11	f	23	36	27	25	13	18	22	21
12	f	21	20	29	26	9.4	14	26	14
13	f	30	27	29	24	24	27	19	24
14	f	25	24	26	23	18	16	18	21
15	f	27	27	26	23	20	19	25	27
16	f	23	23	25	16	12	16	20	22
17	m	25	25	30	27	17	13	19	18
18	m	19	20	22	14	13	18	29	25
19	m	17	17	27	16	10	15	30	27
20	f	30	26	22	20	23	20	25	28
21	f	25	26	20	34	17	19	26	20
22	m	24	23	24	25	18	24	31	29
		CV-intra	CV-inter	CV-intra	CV-inter	CV-intra	CV-inter	CV-intra	CV-inter
	Mean	19	24	23	22	15	17	24	22
	SD	7	5	6	5	5	4	4	5
	Median	20	25	24	23	16	17	25	22

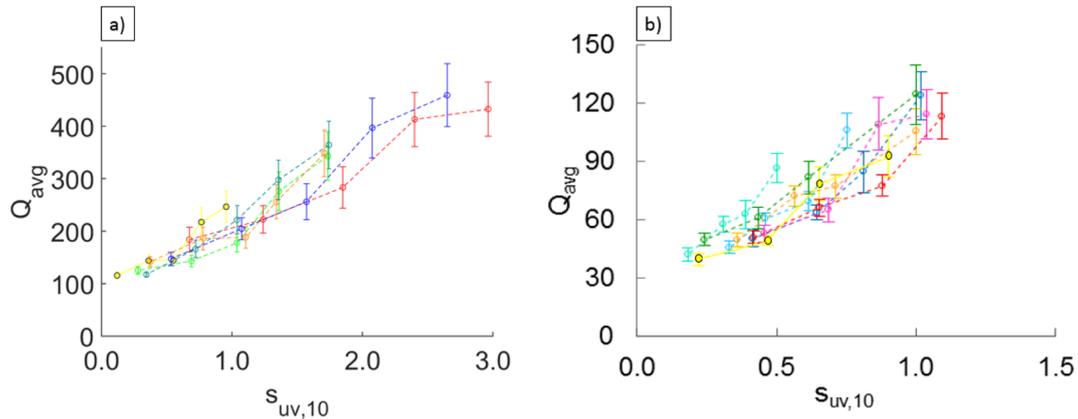


Figure 7 Perceived brightness versus saturation of the stimuli with a fixed neutral background and with the reference stimulus presented in temporal juxtaposition.

a) Belgian setup with LEDs (Stimuli: $L=50\text{ cd/m}^2$; Background: $L=28\text{ cd/m}^2$, $u'_{10}=0.235$, $v'_{10}=0.490$). b) Argentinian setup with projector (Stimuli: $L=10\text{ cd/m}^2$; Background: $L=5.6\text{ cd/m}^2$, $u'_{10}=0.211$, $v'_{10}=0.472$). Error bars are the standard error of the geometric mean.

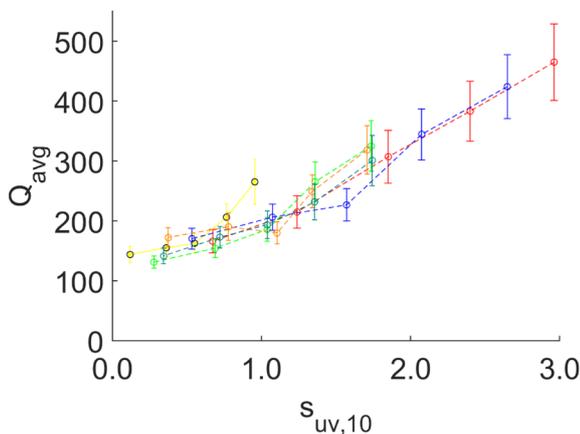


Figure 8 Perceived brightness versus saturation of the stimuli with a fixed neutral background, also serving as reference. Belgian setup with LEDs (Stimuli: $L=50\text{ cd/m}^2$; Background: $L=28\text{ cd/m}^2$, $u'_{10}=0.235$, $v'_{10}=0.490$). Error bars are the standard error of the geometric mean.

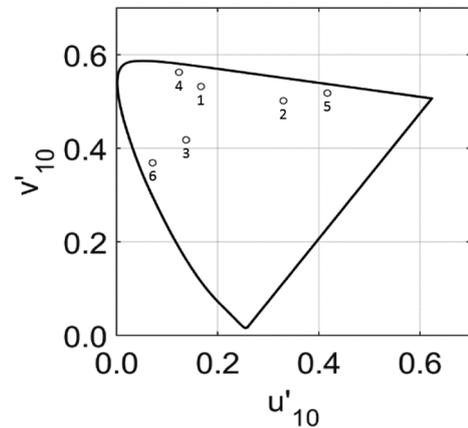


Figure 9 CIE 1976 u'_{10} , v'_{10} chromaticity coordinates of the 6 test stimuli for the paired comparison experiment.

hue. As all test stimuli had the same luminance level in each experimental setup, this increase in perceived brightness is a clear illustration of the Helmholtz-Kohlrausch effect. The brightness of highly saturated red stimuli is perceived 4 times as bright as a neutral stimulus with the same luminance.

When using the background as a reference, the results are very similar as can be seen from Figure 8.

3.2.3 Forced choice paired comparison experiment investigating the Helmholtz-Kohlrausch effect

To investigate the Helmholtz-Kohlrausch effect further a forced choice full paired comparison experiment was set up using the LED based setup. Six different stimuli were selected: three saturated ones and three less saturated ones (Figure 9). Again the luminance of all six stimuli was 50 cd/m^2 and the stimuli were seen in positive luminance contrast against the self-luminous

background with a luminance level of 28 cd/m^2 .

With these six stimuli, thirty different pairs were created and were shown at random to 22 naïve Belgian observers. The two stimuli in one pair were shown in temporal juxtaposition for 10s each. Observers had to answer, after showing them one pair, which stimulus was perceived as the brightest. Observer consistency was checked by counting the number of intransitive triads of assessments: if an observer perceived stimulus 1 brighter than stimulus 2 and 2 brighter than 3, stimulus 1 should be perceived brighter than 3 for each possible combination of 3 stimuli. Twenty of the 22 observers had no inconsistencies at all, two observers only had one inconsistent triad. A generalized linear model modified from the Scheffé method has been applied to the visual data producing a z-score on an interval scale and a standard error for the perceived brightness for each of the 6 stimuli^{21, 22}. The z-score for the perceived brightness is plotted for all 6 stimuli in Figure 10. The standard error ($SE=0.22$) is also shown. All saturated stimuli are perceived significantly brighter than the

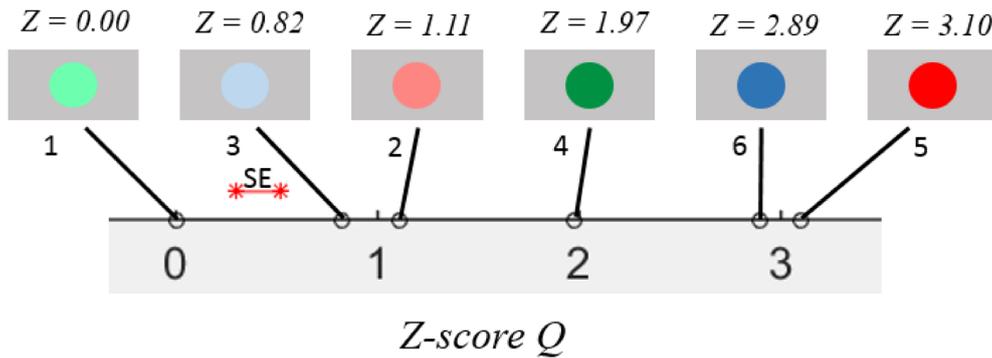


Figure 10 The z-score of brightness perception of the paired comparison experiment for 6 different stimuli. The standard error is represented by SE.

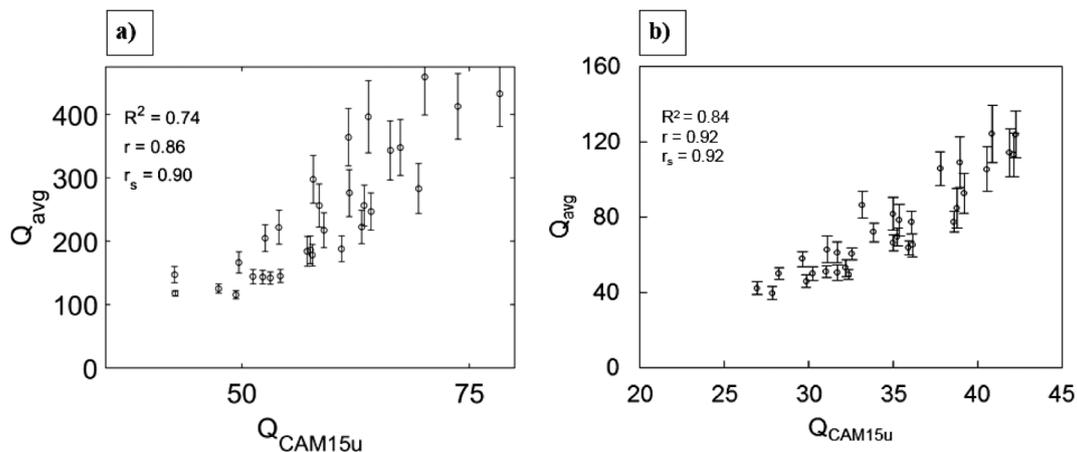


Figure 11 Brightness perception of the average observer (a. Belgian and b. Argentinian) when a reference stimulus is presented in temporal juxtaposition compared with the predicted brightness of the CAM15u model. Error bars are the standard error of the geometric mean.

desaturated ones ($p < 10^{-6}$). The difference between the saturated red and blue stimuli was not significant ($p = 0.37$); the difference between the desaturated red and blue stimulus was ($p = 0.035$).

The results from this paired comparison test on these 6 stimuli having the same luminance (50 cd/m^2) against the self-luminous neutral background of 28 cd/m^2 confirm the results obtained with the magnitude estimation: the brightness perception of the average observer strongly increases with saturation, indicating the presence of a strong Helmholtz-Kohlrausch effect.

3.2.4 CAM15u predictive performance

The predictive performance of the CAM15u model, originally designed for self-luminous stimuli perceived with a dark background, was tested against the visual data obtained for positive contrast self-luminous stimuli presented with a fixed self-luminous background. A comparison of the perceived brightness data for the average observer with the brightness prediction of the CAM15u model, resulted in a Pearson correlation (r_p) equal to resp. 0.86 and 0.92; coefficients of determination (R^2) of resp. 0.74 and 0.84 and a Spearman rank correlation coefficient of resp. (r_s) 0.90 and 0.92 for the Belgian

and Argentinian data. The perceived brightness for the average observer and that predicted by the CAM15u model has been plotted in Figure 11.

Comparing the perceived brightness data for the average observer with the brightness prediction of the CAM97u¹⁾ model and the CAMFu⁵⁾ model, resulted in a coefficients of determination (R^2) of resp. 0.0004 and 0.002 and a Spearman rank correlation coefficient of resp. (r_s) 0.02 and 0.10 for the Belgian data (Figure 12).

Comparing the perceived brightness data for the average observer with the brightness prediction of the CAM97u¹⁾ model and the CAMFu⁵⁾ model, resulted in a coefficients of determination (R^2) of resp. 0.02 and 0.01 and a Spearman rank correlation coefficient of resp. (r_s) -0.12 and -0.07 for the Argentinian data (Figure 13).

The low values of the Spearman correlation coefficient and the low coefficient of determination for all stimuli are striking (Table 2). It is clear that both models perform badly because of the underestimation of the Helmholtz-Kohlrausch effect.

Comparing the hue quadrature from the average observer with the hue quadrature of the CAM15u model, resulted in a Pearson correlation coefficients (r_p) of 0.97

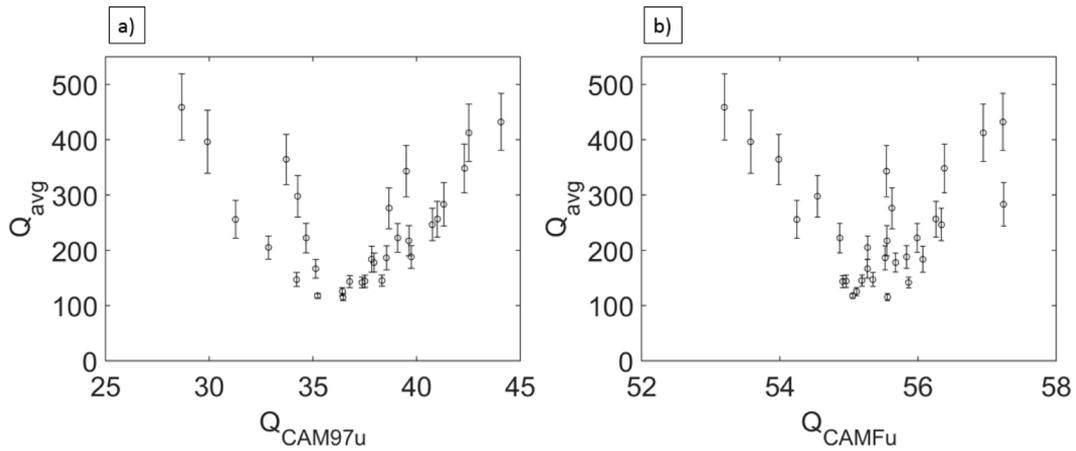


Figure 12 Brightness perception of the average observer compared with the predicted brightness of the CAM97u model (a) and the CAMFu model (b) for the Belgian data.

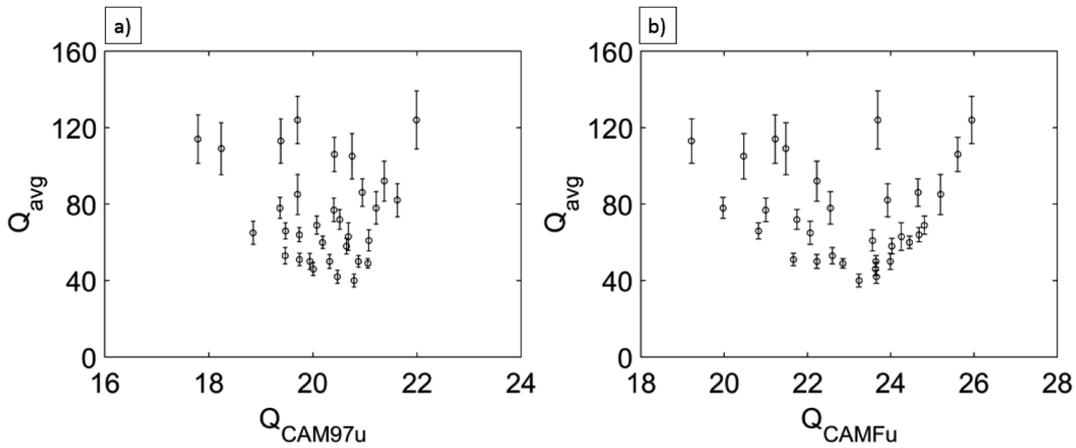


Figure 13 Brightness perception of the average observer compared with the predicted brightness of the CAM97u model (a) and the CAMFu model (b) for the Argentinian data.

Table 2 Overview of the correlation between the ‘average observer’ brightness data and the predictions of the vision models.

	Belgian data		Argentinian data	
	R^2	r_s	R^2	r_s
CAM15u	0.74	0.90	0.84	0.92
CAM97u	0.0004	0.02	0.02	-0.12
CAMFu	0.002	0.10	0.01	-0.07

coefficients of determination (R^2) of 0.94 and a Spearman rank correlation coefficients of (r_s) of 0.97 for the Belgian data. No hue data was collected at the Argentinian lab. Figure 14 shows a plot of the visual versus the predicted hue quadrature.

Finally, for the amount-of-neutral, Pearson correlation coefficients (r_p) of resp. 0.86 and 0.87; coefficients of determination (R^2) of resp. 0.73 and 0.76 and Spearman rank correlation coefficients (r_s) of resp. 0.85 and 0.87 were found. A plot of the visual versus the predicted amount-of-neutral can be found in Figure 15. The large variation in the data for this correlate is clearly visible.

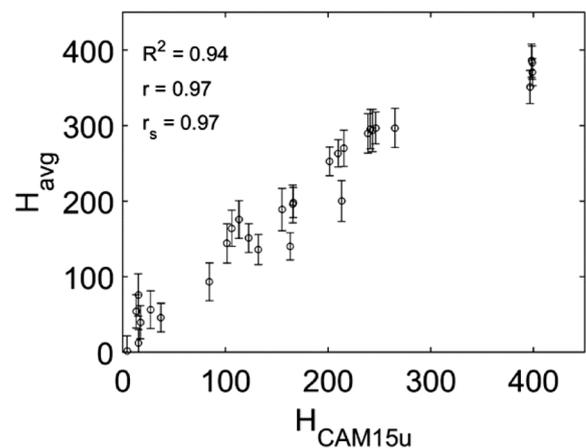


Figure 14 Hue quadrature of the average observer compared with the predicted hue quadrature of the CAM15u model. Error bars are the standard error of the arithmetic mean.

Although amount-of-neutral is certainly more easy to assess for laymen than colourfulness or saturation, this does not lead to a more robust result.

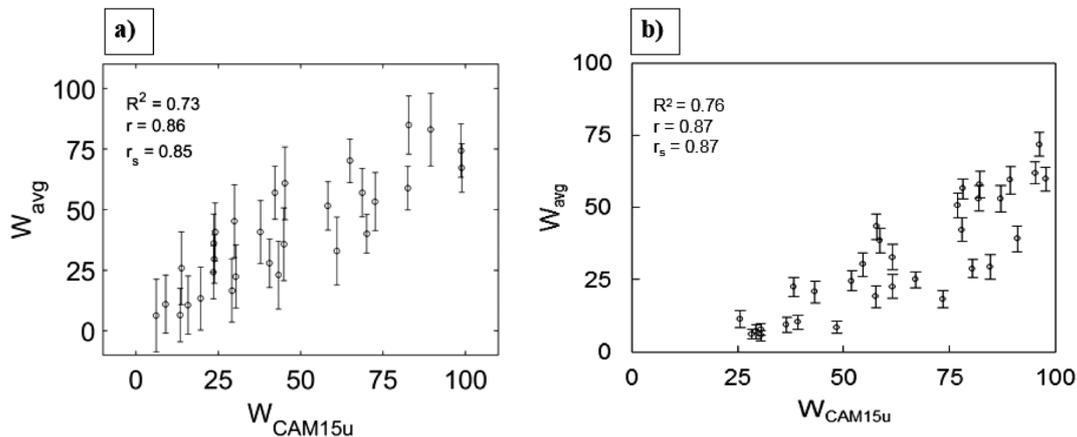


Figure 15 Amount of white of the average observer compared with the predicted amount of white of the CAM15u model (a. Belgian and b. Argentinian). Error bars are the standard error of the arithmetic mean.

4. Conclusions

Recently a model, CAM15u, was developed to predict the brightness, hue, colourfulness and amount-of-neutral of unrelated self-luminous stimuli. In this work similar experiments, as the ones on which CAM15u was based, have been performed, but the stimuli have been presented in positive contrast surrounded by a self-luminous background instead of a dark one. Experiments have been performed in Belgium and in Argentina using two different experimental setups. One with the stimuli generated using LEDs as described in Whithouck et al.⁷⁾ (Belgium) and one where both stimulus and background were generated on a diffusing screen illuminated from the back using a data projector (Argentina).

The Belgian study used thirty stimuli with a fixed luminance of 50cd/m^2 selected at 6 different hues and 5 saturation levels. The Argentinian study used thirty two stimuli with a fixed luminance of 10cd/m^2 selected at 8 different hues and 4 saturation levels. The brightness, hue and amount-of-neutral of these related self-luminous stimuli was assessed by resp. 22 Belgian and 20 Argentinian observers by using the magnitude estimation method. The results of all experiments showed that the strong Helmholtz-Kohlrausch effect (the brightness perception of an observer increases strongly with saturation) observed for unrelated stimuli is still present for related self-luminous stimuli seen in positive contrast with a self-luminous background.

The brightness, hue quadrature and amount-of-neutral ratings for the self-luminous stimuli were found to be well predicted by CAM15u. Although the CAM15u model was developed for unrelated self-luminous colours, it was found to be also capable of accurately predicting the color appearance correlates of related self-luminous colours seen in positive luminance contrast against a self-luminous background.

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References

- (1) Fairchild, M. D.: *Color Appearance Models* (2005). doi: 10.1002/9781118653128
- (2) Hunt, R. W. G., Robert, W. G. and Pointer, M.: *Measuring Colour*. Wiley (2011).
- (3) Luo, M. R. and Hunt, R. W. G.: The structure of the CIE 1997 Colour Appearance Model (CIECAM97s), *Color Res. Appl.*, 23-3, pp. 138-146 (1998). doi: 10.1002/(SICI)1520-6378(199806)23:3<138::AID-COL5>3.0.CO;2-R
- (4) Rich, D. C.: Publication CIE 159: A colour appearance model for colour management systems: CIECAM02, *Color Res. Appl.*, 31-2, pp. 158-158 (2006). doi: 10.1002/col.20198
- (5) Fu, C., Li, C., Cui, G., Luo, M. R., Hunt, R. W. G. and Pointer, M. R.: An investigation of colour appearance for unrelated colours under photopic and mesopic vision, *Color Res. Appl.*, 37-4, pp. 238-254 (2012). doi: 10.1002/col.20691
- (6) Whithouck, M., Smet, K. A. G., Ryckaert, W. R., Deconinck, G. and Hanselaer, P.: Predicting the brightness of unrelated self-luminous stimuli, *Opt. Express*, 22-13, pp. 16298-16309 (2014). doi: 10.1364/

OE.22.016298

- (7) Withouck, M., Smet, K. G., Ryckaert, W. R. and Hanselaer, P.: Experimental driven modelling of the color appearance of unrelated self-luminous stimuli: CAM15u, *Opt. Express*, 23-9, pp. 12045–12064 (2015). doi: 10.1364/OE.23.012045
- (8) International Commission on Illumination. CIE Supplementary System of Photometry. CIE Central Bureau (2011).
- (9) International Commission on Illumination. Fundamental Chromaticity Diagram with Physiological Axes. Part 1. Commission internationale de l'éclairage (2006).
- (10) Leloup, F. B., Pointer, M.R., Dutré, P. and Hanselaer, P.: Luminance-based specular gloss characterization. 2960;2905020(330).
- (11) Moroney, N., Fairchild, M. D., Hunt, R. W. G., Li, C., Luo, M. R. and Newman, T.: The CIECAM02 color appearance model (2002). <http://scholarworks.rit.edu/other/143>. Accessed July 3, 2016.
- (12) Hunt, R. W. G.: A model of colour vision for predicting colour appearance, *Color Res. Appl.*, 7-2, pp. 95–112 (1982). doi: 10.1002/col.5080070207
- (13) Kim, M. H., Weyrich, T. and Kautz, J.: Modeling Human Color Perception under Extended Luminance Levels.
- (14) CIE160: Colorimetry. In: International Commission on Illumination. Colorimetry. Commission Internationale de l'Eclairage, p. 72 (2004).
- (15) Gescheider, G. A.: Psychophysical scaling, *Annu. Rev. Psychol.*, 39-1, pp. 169–200 (1988).
- (16) Yellott, J., Wandell, B. and Cornsweet, T.: The beginnings of visual perception: The retinal image and its initial encoding (1980). <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.228.2909&rep=rep1&type=pdf>. Accessed July 3, 2016.
- (17) Cunningham, D. and Christian, W.: *Experimental Design* (2011). doi: 10.4135/9781412961288.n141
- (18) García, P., Huertas, R., Melgosa, M. and Cui, G.: Measurement of the relationship between perceived and computed color differences, *J. Opt. Soc. Am. A Opt. Image Sci. Vis.*, 24-7, pp. 1823–1829 (2007). doi: 10.1364/JOSAA.24.001823
- (19) Luo, M. R., Clarke, A. A., Rhodes, P. A., Schappo, A., Scrivener, S. A. R. and Tait, C. J.: Quantifying colour appearance. Part I. Lutchi colour appearance data, *Color Res. Appl.*, 16-3, pp. 166–180 (1991). doi: 10.1002/col.5080160307
- (20) Withouck, M., Smet, K. A. G., Ryckaert, W. R., Pointer, M. R., Deconinck, G., Koenderink, J. and Hanselaer, P.: Brightness perception of unrelated self-luminous colors, *J. Opt. Soc. Am. A Opt. Image Sci. Vis.*, 30-6, pp. 1248–1255 (2013). doi: 10.1364/JOSAA.30.001248
- (21) Scheffé, H.: An analysis of variance for paired comparisons, *J. Am. Stat. Assoc.*, 47, pp. 381–400 (1952) doi: 10.1080/01621459.1952.10501179
- (22) Rajae-Joordens, R. and Engel, J.: Paired comparisons in visual perception studies using small sample sizes, *Displays*, 26-1, pp. 1–7 (2005). doi: 10.1016/j.displa.2004.09.003

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