Psycho-physical evaluation of a chromatic model of mesopic visual performance

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Abstract

A chromatic (cone-opponent) model, the CHC model, was developed to predict mesopic detection thresholds for light increments on a mesopic background. In the present work, the psycho-physical testing of the CHC model (and its equivalent photometric model) is shown. The experiment was carried out with quasi-monochromatic (QM) red and QM green light increment stimuli on an achromatic background, and also with the additive mixture of QM red and QM green, a so-called "two-peak" yellow light increment. The method of constant stimuli was used. Detection thresholds (p=0.5) were computed by probit analysis, in terms of threshold increment radiance values. Spectral sensitivity functions of mesopic increment detection thresholds were compared with those of perceived photopic brightness. The application to realistic lighting situations needs further experiments. The CHC model (or a similar model based on the same principle) is suggested to solve the problem of non-additivity in every visual task where a "multi-peak" luminous efficiency function shows the activity of cone opponent mechanisms.

Introduction

As it is well known, the use of $V(\lambda)$ as the basis of photometry results in errors in predicting visual performance in the mesopic range[1]. Mesopic brightness models are based on heterochromatic brightness matching predicting the perceived brightness of steady above-threshold stimuli. However, visual performance (detection, recognition, or reaction time) based mesopic models have a different form because the task of the observer is significantly different from brightness matching and the visual system operates at or near threshold. Current models of mesopic visual performance are so-called "photometric" models in the sense that they use spectral integration hence spectral additivity is assumed. For mesopic visual performance, "multi-peak" spectral sensitivity curves (having several local maxima across the visible spectrum) were found[1,2,11]. The reason was claimed to be the influence of chromatic (opponent) channels[2,11]. It was also shown that the effect of the opponent mechanisms is associated with spectral non-additivity[3]. A chromatic (cone-opponent) model (called CHC model in this paper) was developed to account for non-additivity[3].

CHC model and its equivalent photometric model

The CHC model computes a descriptor of mesopic increment detection performance. This descriptor is called CHC (from the abbreviation of chromatic conspicuity). CHC is related to the conspicuity of the visual target (i.e. the light increment) at or near the detection threshold. CHC is restricted to describe the conspicuity of a 2° (or similar size) quasi-stationary light increment or visual target (its time of appearance shall be greater than or equal 2s) on a large, fixed, uniform mesopic background. The CHC model is defined as follows:

$$CHC=b_1\Delta V^*+b_2\Delta V'+b_3\Delta S+b_4|\Delta L-1.4\Delta M| \qquad (1)$$

where $\Delta V^*=\int V^*(\lambda)\,\Delta\chi(\lambda)d\lambda$, $\Delta V'=\int V'(\lambda)\,\Delta\chi(\lambda)d\lambda$, $\Delta S=\int S(\lambda)\,\Delta\chi(\lambda)d\lambda$, $\Delta L=\int L(\lambda)\,\Delta\chi(\lambda)d\lambda$, $\Delta M=\int M(\lambda)\,\Delta\chi(\lambda)d\lambda$, and $\Delta\chi(\lambda)$ is the absolute spectral power distribution (SPD) of the light increment added to the background. $V^*(\lambda)$ is the Sharpe et al. luminous efficiency function[4], $V'(\lambda)$ is the CIE scotopic luminous efficiency curve, and $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$ are the Stockman and Sharpe (2000) 2° cone fundamentals[5]. The functions $V^*(\lambda)$, $V'(\lambda)$, $L(\lambda)$, $M(\lambda)$, and $S(\lambda)$ are re-normalized at their maxima. They are expressed on the linear energy scale. The factor 1.4 in Eq. (1) represents best fit to a set of experimental spectral increment threshold detection sensitivity curves[2,6,12]. All spectral integrals are computed between 380nm and 780nm. The parameter set {b_1, b_2, b_3, b4} depends on the retinal eccentricity of the target as well as on the absolute SPD of the background. It can be obtained from psycho-physical increment detection threshold measurements. The detection threshold is characterized by CHC=1 from which the threshold increment radiance $\Delta R_{CHC,th}$ can be computed if the relative SPD of the light increment is known.

A conventional photometric model (in the sense that it uses direct spectral integration with a luminous effciency function) equivalent to the CHC model can also be formulated:

$$C=\int V_{mes}(\lambda)\,\Delta\chi(\lambda)d\lambda \qquad \text{with } V_{mes}(\lambda)= b_1V^*(\lambda)+b_2V'(\lambda)+b_3S(\lambda)+b_4|L(\lambda)-1.4M(\lambda)| \qquad (2)$$

In Eq. (2), C is target conspicuity, modelled by the photometric model, and the parameter set {b_1, b_2, b_3, b_4} is the same as in Eq. (1). The detection threshold is characterized by C=1 from which the threshold increment radiance $\Delta R_{C,th}$ can be computed if the relative SPD of the light increment is known.

The magnitude of spectral non-additivity (NA) of the photometric model can be quantified by

$$NA = \Delta R_{CHC,th} - \Delta R_{C,th} \qquad (3)$$

NA can be expressed e.g. in $\mu Wsr^{-1}m^2$ units. NA>0 means that the photometric model underestimates the detection threshold. This is not a desirable property for lighting design and lighting evaluation because it creates an unsafe condition i.e. the visual target cannot be detected. Below, the results of a psycho-physical experimental test of the CHC model (Eq. (1)) and its equivalent photometric model (Eq.(2)) is shown.

Experimental Method

The achromatic background was a large projection wall illuminated by a white phosphor LED lamp at 0.5cd/m^2 (x=0.32; y= 0.34, CCT=6000K). The visual target was a 2° filled disk presented 20° off the visual axis. It was a light increment projected onto the background. All physical measurements were carried out by a calibrated PR 705 spectro-radiometer. Both observers (MN and EK) had good colour vision. In the fixation centre, red numbers (2°) were presented to control the subject's fixation. If the observer missed the central target then her/his off-axis result was discarded. The observer's task was to find the detection threshold by the method of constant stimuli. In one observation, 199 constant disks of different light increment radiance values appeared, each of them for 2s, and then, the observer had to tell whether she/he had seen the target. The frequencies of "yes" answers were recorded as a function of the radiance of the light increment on the background. Observations were carried out with red (615nm) and green (540nm) quasi-monochromatic (QM) targets (of spectral bandwidth of 10nm), and also with a "two-peak" yellow target i.e. the additive mixture of the red and green QM targets projected onto the same location on the background by two projectors. The 2 wavelengths (615nm and 540nm) are near to the maxima of the |L-1.4M| mechanism.

Results and Discussion

A detection threshold was defined as a radiance value of the light increment necessary to obtain a detection frequency of p=0.5. Measured red, green, and yellow increment detection threshold radiance data ($\Delta R_{meas,th}$) were obtained by SPSS® probit analysis with p=0.5. These data are shown in Table 1A. From these data, the parameter set {b_1, b_2, b_3, b_4} was estimated, see Table 1B. Only b_1 and b_4 were changed with Excel Solver®. The factors b_2=0.51987b_1 and b_3=0.53226b_1 were used. Latter factors resulted from a previous study[6]. Threshold increment radiance data were predicted ($\Delta R_{CHC,th}$ and $\Delta R_{C,th}$) by Eqs. (1)-(2) using the CHC=1 and C=1 criteria, respectively, see Table 1A. Threshold radiance data are shown in μW $sr^{-1}m^{-2}$ units.

Table 1A. Measured (mean and 95% confidence limits) and predicted red, green, and yellow increment threshold radiance data

	Threshold radiance data $\Delta R_{meas,th}$, $\Delta R_{CHC,th}$, and $\Delta R_{C,th}$								
Obs.	**Red (QM 615nm)**			**Green (QM 540nm)**			**Yellow ("2-peak")**		
	Measured	Predicted		Measured	Predicted		Measured	Predicted	
	$\Delta R_{meas,th}$	CHC	C	$\Delta R_{meas,th}$	CHC	C	$\Delta R_{meas,th}$	CHC	C
MN	19.7 (13.5, 23.3)	22.4	22.4	14.2 (12.5, 15.5)	12.3	12.3	25.9 (23.9, 27.5)	28.1	15.8
EK	33.2 (31.3, 34.6)	34.5	34.5	18.9 (17.7, 20.6)	17.7	17.7	35.6 (33.1, 40.7)	36.7	23.3

Table 1B. Model parameter sets {b_1, b_2, b_3, b_4}

Obs.	**Model parameters**			
	b_1	b_2	b_3	b_4
MN	0.0342	0.0178	0.0182	0.0392
EK	0.0274	0.0142	0.0146	0.0222

Following can be seen from Table 1A:

1. For QM increment SPDs (red and green), the CHC=1 and C=1 criteria yield the same detection threshold radiance values ($\Delta R_{CHC,th}$=$\Delta R_{C,th}$ hence NA=0). Mathematically, it is easy to see that, for any QM increment SPD, CHC=C[3] (with a good approximation provided that the bandwidth of the QM radiation is small enough);
2. For the yellow light increment, CHC provides a better approximation for the measured detection threshold than C. NA=28.1-15.8=12.3μW$sr^{-1}m^{-2}$ for observer MN, and NA=36.7-23.3=13.4μW$sr^{-1}m^{-2}$ for observer EK, see Eq.(3). The obtained yellow NA values show that the photometric model underestimates the detection threshold radiance;
3. The agreement with the experimental data is not perfect. The reason may be the limited accuracy of the linear signal summation model used in Eqs. (1)-(2). Other summation models will be presented in a subsequent paper.

The spectral mesopic detection threshold sensitivity curves $V_{mes}(\lambda)$ modelled by Eq. (2) are shown in Figure 1, with the 2 different parameter sets {b_1, b_2, b_3, b_4} of observers MN and EK taken from Table 1B. The parameter sets {b_1, b_2, b_3, b4} were re-normalized so that the curves are equal 1 at their maxima. Similar model curves (see Eq. (2)) were also fitted to the CIE $V_{b,2}$ and $V_{b,10}$ photopic brightness data[7]. This is also shown in Figure 1. Model parameters are compared in Table 2.

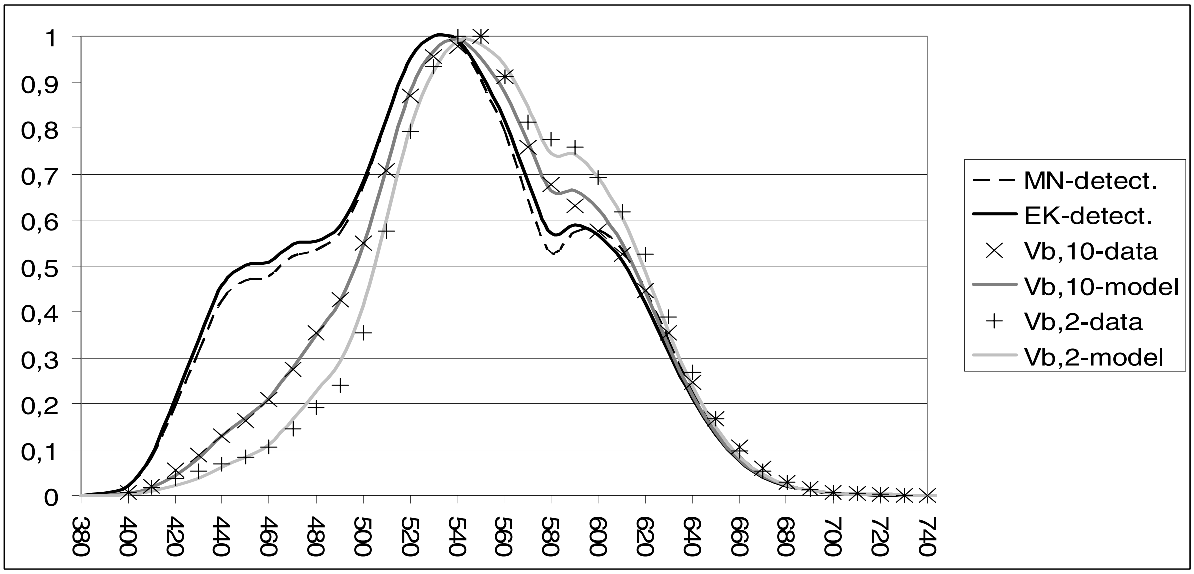

Figure 1. Spectral mesopic detection threshold sensitivity curves $V_{mes}(\lambda)$ modelled by Eq. (2), for observers MN and EK (see Table 1B). Similar model curves fitted to the CIE $V_{b,2}(\lambda)$ and $V_{b,10}(\lambda)$ data[7]. Model parameters (see Eq.(2)) are shown in Table 2.

Table 2. Re-normalized model parameters (see Eq. (2)) for observers MN and EK (mesopic increment detection threshold criterion, see Table 1B), and for the CIE $V_{b,2}(\lambda)$ and CIE $V_{b,10}(\lambda)$ data (photopic brightness criterion, averaged values of 10° and 2° luminous efficiencies, Table 6.1[7])

Model parameters (see Eq.(2))	Observer			
	MN	EK	"CIE $V_{b,2}$"	"CIE $V_{b,10}$"
b_1 (V*)	0.523	0.577	0.820	0.703
b_2 (V')	0.272	0.300	0.000	0.172
b_3 (S)	0.278	0.307	0.000	0.016
b_4 (|L-1.4M|)	0.599	0.469	0.396	0.403

Following can be seen from Table 2 and Figure 1:

1. Observers MN and EK have similar spectral sensitivity curves for mesopic increment threshold detection;
2. The rod (b_2) and S-cone (b_3) components are missing from the $V_{b,2}(\lambda)$ curve but not from $V_{b,10}(\lambda)$;
3. The CIE $V_{b,2}$ and $V_{b,10}$ data[7] can be predicted with reasonable accuracy by a similar model to Eq.(2);
4. The values of b_4 (0.396 and 0.403) indicate the spectral non-additivity of photopic brightness (a well-known fact in literature).

CIE Publication No. 75[7] mentions that "further work is required to evaluate lights with compound spectra with allowance for additivity failure". It may be possible to model perceived brightness (Q) by an equation similar to Eq.(1) and by using the parameters of Table 2. This will be shown in a subsequent paper.

Recently, a similar model to Eq.(2) was found to account for spectral detection and recognition threshold sensitivity and also for discomfort glare spectral sensitivity[8, 9]. The difference between this model[8] and the present model (Eq. (2)) is that this model[8] uses an S-(L+M) type term while Eq. (2) uses standalone $S(\lambda)$ similar to [2, 10, 11].

The CHC model (Eq.(1), or a similar model based on the same principle) is suggested to solve the problem of non-additivity in every visual task where a "multi-peak" luminous efficiency function shows the activity of cone opponent mechanisms.

An important application of the CHC model (Eq.(1)) is the evaluation of real mesopic lighting scenes. In these scenes, the conspicuity of achromatic or coloured visual objects of composite SPDs emerging from the mesopic background can be predicted. If the conspicuity of the object is above a critical value (e.g. CHC=2) then the object can be detected safely. As shown above, the "photometric" predictor *C* of Eq.(2) is not usable because it tends to overestimate the conspicuity of these objects in the detection task due to spectral non-additivity. This effect is similar to the one shown in Figure 9[11] where the photometric model of Eq.(12)[11] underestimates the measured reaction times thus overestimating the conspicuity of the targets and suggesting that a CHC-type formula (similar to Eq.(1)) should be used to predict reaction time.

An example of a real mesopic scene can be seen in Figure 2. In this scene, the visual target appeared 5.4° left to the optical axis. This angle is different from the retinal eccentricity used in the present experiment (20°, see Section 3 above). As a strong dependence of the parameter set (b_1, b_2, b_3, b_4) on retinal eccentricity is expected, the parameter sets in Table 1B should not be applied to Figure 2 to predict the value of CHC for that circular visual target. The dependence of (b_1, b_2, b_3, b_4) on retinal eccentricity and background SPD will be discussed in a subsequent paper. Also, it is not yet clear how to weight the spectral properties of the background across space to be able to compute a characteristic parameter set (b_1, b_2, b_3, b_4). Our experiments on the above issues are currently underway.

Figure 2. A mesopic road lighting scene with a circular visual target (left picture, below the white arrow). The scene was measured at night by a video-photometer with 4 filters (X, Y, Z, and V'). The target appeared at 5.4° left to the optical axis and its diameter was 2.3°. Right picture: photopic luminance distribution next to the target.

Keywords
Mesopic vision, visual performance, spectral non-additivity, conspicuity, brightness perception

Acknowledgement
Authors would like to acknowledge Prof. János Schanda for his valuable scientific comments. One author (PB) would like to acknowledge the Alexander von Humboldt Foundation for supporting this work.

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