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Visual properties of metameric blacks beyond cone vision

Françoise Viénot,^{1,*} Hans Brettel,²

¹*Centre de Recherche sur la Conservation des Collections, Muséum National d'Histoire Naturelle, 36 rue Geoffroy Saint-Hilaire, F-75005 Paris, France*

²*CNRS LTCI, Telecom ParisTech, 46 rue Barrault, F-75013 Paris, France*

*Corresponding author: vienot@mnhn.fr

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The generic framework of metamerism implies that the number of sensors is smaller than the dimension of the stimulus. The metameric black paradigm was introduced by Wyszecki [Farbe, **2**, 39 (1953)] and developed by Cohen and Kappauf [Am. J. Psychol. **95**, 537 (1982)]. Within a multi-receptor and multi-primary scheme, we investigate how far the choice of illumination can isolate a photo-receptor response. The spectral profiles of the fundamental metamers that correspond to a collection of (x, y) values over the chromaticity diagram is shown. When the luminance is set at a fixed value, the relative excitation of the melanopsin cells and of the rods elicited by the fundamental metamers varies over the chromaticity diagram. The range of excitation of the melanopsin cells and of the rods that could be achieved at a given chromaticity, by manipulating the metameric black content, is examined. When only the melanopsin excitation is manipulated, the range of melanopsin excitation that can be achieved is rather limited. On the chromaticity diagram, the largest range of variation of the rods and the melanopsin cells excitation is obtained for (x, y) chromaticity coordinates near (1/3, 1/3). Extension of Cohen's procedure to rod and cone metamers is proposed. The higher the number of spectral bands, the wider the choice of metameric lights.

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1. CONTEXT AND INTRODUCTION

Metamerism is fundamental to colour science. It refers to the phenomenon by which stimuli appear identical in colour but have different spectral power distributions. The term “metamer” (“Metamere Farben”), transposed from chemistry science into the colour field by Ostwald [1], is most often employed within the context of trichromacy. The definition given by Kaiser and Boynton [2] “Two stimuli, which are physically different but visually indistinguishable, are called metamers” is not only valid when cone vision is operative but is also applicable to other sets of visual receptors. The generic framework of metamerism implies that the number of sensors is smaller than the dimension of the stimulus. Thus any colour stimulus function projects into the sensor space in a well-defined response but the reverse projection is loosely defined.

Metamers are usually defined with respect to cones whereas they may excite differently other photoreceptors that are present in the retina. Rods convey the night-time image information. A few retinal ganglion cells contain a photosensitive pigment named melanopsin. The so-called “intrinsically photosensitive retinal ganglion cells” (ipRGC) project to the pretectum and convey information that is not devoted to image formation but signal light for unconscious visual function such as the pupillary reflex and photo-entrainment of the circadian rhythm [3,4]. In addition to being intrinsically photosensitive, giant melanopsin ganglion cells are strongly activated by rods and cones and project to the lateral geniculate nucleus [4].

The visual sensitivity range of ipRGCs partly covers the rod intensity response range and parallels the cone response range [4]. Isolating responses of one or another type of photoreceptor requires specific paradigms. The time taken to reach peak in the ERG from the responses of the ipRGCs significantly differs from that of rods and cones [5]. Nevertheless, due to overlap of spectral sensitivity for cones, rods and melanopsin cells, assessing the relative contribution of the receptor types to image and non-image visual functions is difficult.

The three-dimensionality of colour stimuli has often been questioned at photoreceptor level. Considering that rods and/or melanopsin cells are responsive, the visual response is no longer three-dimensional [6,7,8]. It is four- or five-dimensional. Trichromacy no longer holds in colour matching at low luminance levels or in the peripheral visual field when rods are liable to be active [9,10,11,12]. Following the recent discovery of the melanopsin photopigment, it was proposed that metamers could successfully be used to stimulate ipRGCs independently of cone mechanisms using a silent-substitution technique with four-primary stimulation [13]. At high photopic levels, above rod saturation, detection threshold measurements deviate from trichromatic theory. Explaining peripheral sensitivity in threshold measurements and sensitivity to rapid flickering lights requires absorptions in four, not three, photopigment classes. The most likely hypothesis is that melanopsin absorption influences sensitivity [14]. Considering that the perceived brightness of light sources is not always predicted by their respective luminance, Brown et al. [15], using four primary stimuli silent for cones, above rod saturation, and a

two-interval alternative forced-choice procedure, provided evidence that healthy human subjects perceive greater brightness as melanopsin excitation increases.

The metamer black paradigm was introduced by Wyszecki in 1953 [16]. It hypothesizes that any stimulus can be decomposed into a fundamental metamer and a metamer black. In 1982, Cohen initiated a series of articles to describe all potential metamers as vectors [17,18]. His mathematical method has been applied to predicting the illuminant-independent properties of reflectance functions [19], to studying the structure and reducing the dimensionality of colour space [20,21,22,23], to founding theories of colour constancy [24], to reducing the number of channels in multi-spectral imaging [25], and to estimating the spectral sensitivities of colour camera sensors [26].

The metamer black paradigm gains advantage as soon as receptors other than cones are sensitive to visible light. In a previous paper, we exploited Cohen's method in the case of multi-band illumination obtained with independent colour LEDs. Here, within the same multi-receptor and multi-primary scheme, we investigate how far the choice of illumination can isolate one or another receptor response.

2. METAMERIC BLACKS

A. Wyszecki's view

We know that, even though metamer colour stimuli have different spectral power distributions, they excite the three families of cones identically. They have identical tristimulus values such as L_{10} , M_{10} , S_{10} , referring to the long-wave sensitive, middle-wave sensitive and short-wave sensitive cone excitations, or $X_{F,10}$, $Y_{F,10}$, $Z_{F,10}$, in the CIE fundamental colorimetric system for a 10 degree field of view currently under development by the CIE, available in the database of the Colour & Vision Research Laboratory at www.cvr.org. Wyszecki [16,27] presented the view that the spectral power distribution of metamers consists of two component spectral distributions:

- The fundamental distribution, associated with the tristimulus values and common to all metamers of a metamer suite. The fundamental distribution is named "fundamental metamer".
- A secondary distribution, unique to each metamer (and in every case having tristimulus values of (0, 0, 0). It is invisible; it evokes no colour sensation; it is "black" with respect to colour sensation. The secondary distribution is a "metamer black".

Wyszecki mentioned that E. Hellmig had described the metamer black concept already earlier [16, footnote 16]. It is of interest to note that the qualifying term "black" is to be interpreted colorimetrically, as for luminous colours with tristimulus values equal to zero, and in no way as a perceptual attribute belonging to a surface of low reflectance that appears black in relation to a bright surround [28].

As the metamer black component contributes nothing to the colour specification or the perceived colour, the spectral power distribution necessarily involves negative values at some wavelengths along with positive values at others.

The concept of metamer black has been illustrated by Wyszecki [29]. Colour-matching experiments evidence that any stimulus can be matched by the additive mixture of three appropriately selected primary colours in appropriate amount. The case of monochromatic lights implies a slight modification of the experimental setting. When the experiment is performed

with the maximum saturation method, one primary colour should be added to the monochromatic light to successfully match the additive mixture of the other two primaries. Since in colorimetry, stimuli obey the rules of linear algebra, subtracting one mixture from the other yields a null stimulus, i.e. a stimulus that evokes no cone response. Following such construction, Wyszecki proposed an independent set within which each metamer black contains only four reflectance values different from zero at the position of the experimental spectral primaries, the fourth one, being always equal to 1.0, varying its position in the spectrum from one metamer black to the other [27]. In the wake of this experimental example, Wyszecki determined further metameric blacks by producing linear combinations of the original set. Wyszecki's first proposal was restricted to the division of any stimulus into two unique components, the fundamental metamer and the residual, i.e. a metamer black. Practically, Wyszecki proposed a method for the realization of a large number of metameric colours, which was based on a precalculated set of linearly independent metameric blacks.

B. Generating metamers from metameric blacks: the Cohen and Kappauf procedure

As Cohen commented, "Wyszecki did not isolate even a single fundamental" [18]. Nevertheless, he did compute "residuals" by taking the difference between an initial stimulus and its matching stimulus.

Cohen and Kappauf, in 1982 [17], presented a procedure for accomplishing the decomposition of any stimulus into the fundamental metamer and the "residual" component. The fundamental metamer is obtained with the help of an orthogonal projection, named matrix **R**. The difference between the stimulus power distribution and the fundamental metamer function provides the residual component, which is the metamer black function of the stimulus.

Further, the orthogonal projection described by Cohen and Kappauf allows calculating a base of metameric blacks from which any potential metamer black is a linear combination. Cohen has illustrated the residuals of six selected monochromatic stimuli [18, fig. 8]. The whole metamer black base, computed using 41 spectral tristimulus values and obtained by subtracting matrix **R** from the identity matrix, is shown in figure 1. Like any metamer black, every stimulus from the base has positive and negative values.

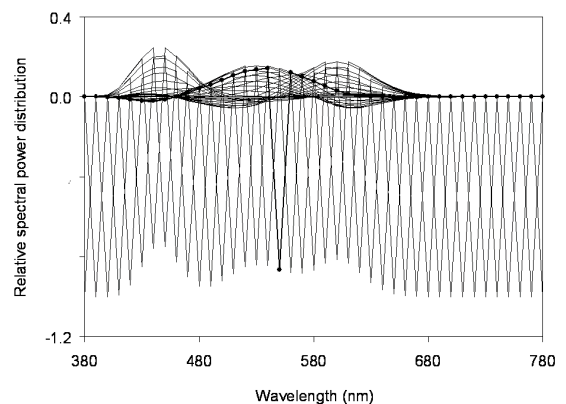


Fig. 1 Relative spectral power distribution of the metameric blacks for 41 monochromatic stimuli. In bold: metamer black corresponding to 550 nm.

As Cohen pointed out, the metameric black base is unique because it solely relies on the cone fundamentals of the colorimetric observer. Once the \mathbf{R} matrix is calculated, all metameric black spectra are accessible. The strength of the \mathbf{R} matrix method is that it produces a base of orthogonal vectors that allows to study the occurrence of every metamer with respect to human cone vision.

As the computational procedures for the separation of any stimulus \mathbf{N} into its fundamental component \mathbf{N}^* and its metameric black component \mathbf{B}

$$\mathbf{N} = \mathbf{N}^* + \mathbf{B} \quad (1)$$

by means of the matrix \mathbf{R} are given in full detail by Cohen and Kappauf [17], we here refer to their presentation.

By uniformly sampling the spectrum of a visual stimulus into k equal wavelength intervals, any stimulus can be represented by a $k \times 1$ dimensional vector \mathbf{N} of its radiometric power distribution.

$$\mathbf{N} = [N_{\lambda 1} N_{\lambda 2} \dots N_{\lambda k}]^T.$$

Using a $k \times 3$ matrix \mathbf{A} representing an equally sampled version of observer's colour-matching functions, tristimulus values \mathbf{T} are obtained as a 3×1 dimensional vector by the product

$$\mathbf{T} = \mathbf{A}' \mathbf{N}. \quad (2)$$

E.g. for the case of the CIE fundamental colorimetric system for a 10 degree field of view currently under development by the CIE [30], \mathbf{A}' is the transpose of

$$\mathbf{A} = \begin{bmatrix} \mathbf{X}_{F,10} & \mathbf{Y}_{F,10} & \mathbf{Z}_{F,10} \end{bmatrix} \quad (3)$$

where each of $\mathbf{X}_{F,10}$, $\mathbf{Y}_{F,10}$, $\mathbf{Z}_{F,10}$ are $k \times 1$ dimensional vectors representing the 10-deg colour-matching functions sampled at k equal wavelength intervals.

As \mathbf{A} is a $k \times 3$ matrix, eq. (2) provides a mapping from a usually huge k -dimensional space of spectral power distribution functions \mathbf{N} into only three-dimensional colour specifications \mathbf{T} .

Because of this dramatic reduction of dimensionality, there exists many different spectral functions \mathbf{N}_i ($i = 1 \dots m$) which all have the same tristimulus values \mathbf{T} .

$$\begin{aligned} \mathbf{A}' \mathbf{N}_1 &= \mathbf{A}' \mathbf{N}_2 = \dots = \mathbf{A}' \mathbf{N}_i \\ &= \dots \mathbf{A}' \mathbf{N}_m = \mathbf{T} \end{aligned}$$

Premultiplying each of these 3×1 dimensional vectors by the $k \times 3$ matrix $\mathbf{A}(\mathbf{A}' \mathbf{A})^{-1}$ produces a $k \times 1$ dimensional vector \mathbf{N}^*

$$\begin{aligned} \mathbf{A}(\mathbf{A}' \mathbf{A})^{-1} \mathbf{A}' \mathbf{N}_1 &= \dots \\ &= \mathbf{A}(\mathbf{A}' \mathbf{A})^{-1} \mathbf{A}' \mathbf{N}_m \\ &= \mathbf{A}(\mathbf{A}' \mathbf{A})^{-1} \mathbf{T} = \mathbf{N}^* \end{aligned} \quad (4)$$

where all the \mathbf{N}_i are different metamers for the same three-dimensional colour specification \mathbf{T} , and \mathbf{N}^* is the fundamental metamer.

The last equality $\mathbf{A}(\mathbf{A}' \mathbf{A})^{-1} \mathbf{T} = \mathbf{N}^*$ of eq. (4) allows computing the fundamental metamer \mathbf{N}^* for any given colour specification \mathbf{T}

$$\mathbf{N}^* = \mathbf{A}(\mathbf{A}' \mathbf{A})^{-1} \mathbf{T}. \quad (5)$$

In the following section 3.A., we show the results obtained by eq. (5) to compute fundamental metamers for different points $(x_{F,10}, y_{F,10})$ of the chromaticity diagram (Fig. 2).

In order to do this, we set

$$\mathbf{T} = (Y_{F,10} / y_{F,10}) \begin{bmatrix} x_{F,10} \\ y_{F,10} \\ 1 - x_{F,10} - y_{F,10} \end{bmatrix}$$

where $Y_{F,10}$ is the luminance and $(x_{F,10}, y_{F,10})$ are the chromaticity coordinates in the CIE fundamental colorimetric system for a 10 degree field of view.

Equation (5) has a further very useful consequence, described by Cohen and Kappauf [17]. By substituting $\mathbf{A}' \mathbf{N}$ from eq. (2) for \mathbf{T} in eq. (5), we get

$$\mathbf{N}^* = \mathbf{A}(\mathbf{A}' \mathbf{A})^{-1} \mathbf{A}' \mathbf{N}. \quad (6)$$

With \mathbf{R} defined as the matrix

$$\mathbf{R} = \mathbf{A}(\mathbf{A}' \mathbf{A})^{-1} \mathbf{A}' \quad (7)$$

eq. (6) reduces to

$$\mathbf{N}^* = \mathbf{R} \mathbf{N} \quad (8)$$

where \mathbf{R} is a symmetric $k \times k$ matrix.

Although the immediate role of matrix \mathbf{R} is to produce the fundamental metamer \mathbf{N}^* from any spectral power distribution \mathbf{N} , it also allows to compute the associated metameric blacks \mathbf{B} .

By substituting $\mathbf{R} \mathbf{N}$ from eq. (8) for \mathbf{N}^* in eq. (1), we get

$$\mathbf{N} = \mathbf{R} \mathbf{N} + \mathbf{B}$$

and further

$$\mathbf{B} = \mathbf{N} - \mathbf{R} \mathbf{N}. \quad (9)$$

By introducing the $k \times k$ identity matrix \mathbf{I} , equation (9) can be written as

$$\mathbf{B} = \mathbf{I} \mathbf{N} - \mathbf{R} \mathbf{N}$$

and further

$$\mathbf{B} = (\mathbf{I} - \mathbf{R}) \mathbf{N}. \quad (10)$$

By designating the $k \times k$ matrix $(\mathbf{I} - \mathbf{R})$ as \mathbf{R}_B , we obtain an equation which directly provides the metameric black \mathbf{B} for any spectral power distribution \mathbf{N}

$$\mathbf{B} = \mathbf{R}_B \mathbf{N}. \quad (11)$$

3. PROPERTIES OF THE FUNDAMENTAL METAMER

A. Fundamental metamers over the chromaticity diagram

There exists only one fundamental metamer that corresponds to a given colour specification. As colour is three-dimensional, the fundamental metamer is three-dimensional as well. Therefore, the whole colour gamut can be described and filled with uniquely defined fundamental stimuli.

As a consequence, ignoring the radiance of the stimulus makes it possible to establish a unique correspondence between the relative spectral power distribution of the fundamental metamer and a point of the chromaticity diagram.

The chromaticity diagram can be tiled with uniquely defined fundamental metamers. In order to present a consistent picture of their relative spectral power distribution, some normalisation is necessary. When the luminance is set at a fixed value $Y_{F,10} = 100$, the figure (fig. 2) shows the spectral profiles of the fundamental metamers that correspond to a collection of $(x_{F,10}, y_{F,10})$ values over the chromaticity diagram. The fundamental metamers of desaturated colours have positive and bimodal spectral power distributions. Conversely, for colours of high purity, the spectral power distribution may have positive and negative values, which means that some

fundamental metamer may not be materialized physically. According to equation (1), the fundamental metamers at spectral loci, accurately described by the function **(N-B)**, present three lobes.

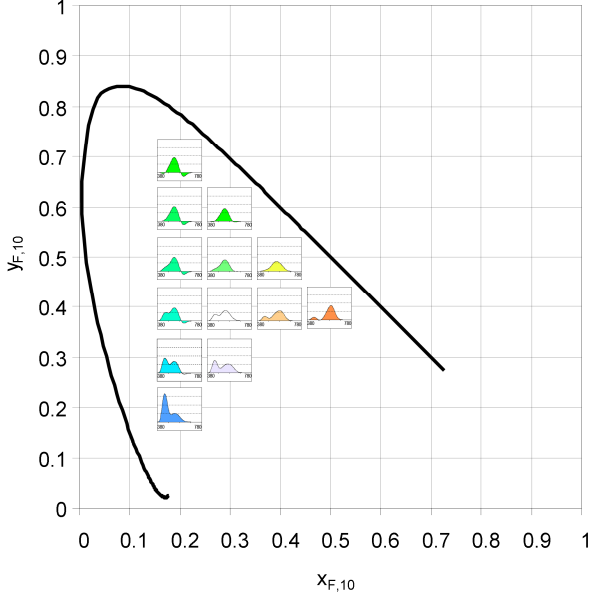


Fig. 2 (Color online) Relative spectral power distribution of fundamental metamers, at a number of chromaticity coordinates.

B. Rod and ipRGCs visual responses to fundamental metamers

We know that any stimulus can be considered as a sum of two components, the fundamental metamer and the “residual” named “metameric black”. Thus, the effect of the stimulus on a photoreceptor or on a photosensitive pigment can result from the addition of individual effects of the components.

1. Rod and ipRGC action spectra

Computing the rod or ipRGC response to fundamental metamers requires us to know their action spectra. The rod action spectrum conforms to the relative spectral responsivity function $V(\lambda)$ of the CIE standard photometric observer, for scotopic vision [31].

The CIE [30] has developed a framework for deriving any set of cone fundamentals which has proved to be a powerful tool to investigate genetic polymorphism [32] and individual variability [33], and can serve further for deriving the action spectrum of other visual receptors, once the photopigment optical density spectrum is available. In previous papers, we proposed to reconstruct the action spectrum of the ipRGCs at the corneal plane, peaking at 490 nm [34,35], considering the following parameters. After Dacey et al. [4], the relative quantal sensitivity of giant melanopsin ganglion cells is well fitted by a vitamin A1 based photopigment nomogram with a peak at 482 nm. Applying the nomogram rule and the CIE framework, we started with the low density absorbance spectrum of the middle-wave sensitive visual pigment expressed in photons [36] and applied a shift of the template along the $\log(1/\lambda)$ axis, so as to position the peak at 482 nm. This gives the low optical density spectrum of melanopsin. Because dendrites and cell bodies of ipRGCs are thin and the density of melanopsin is small compared with the cone external segment [37] we could assume a small optical density

(equal to 0.1) for the photopigment and obtain the spectral sensitivity of the melanopsin cells. No correction was introduced for macular pigmentation, since the incoming light reaches the ipRGCs before it encounters the macular pigment. Finally, we corrected the spectral sensitivity of the melanopsin cells for pre-retinal filters using the lens spectral absorbance as proposed by the CIE for young observers. This operation yielded the action spectrum for exciting melanopsin cells.

2. Rod pigment and melanopsin excitation over the chromaticity diagram, produced by the fundamental metamers

Every fundamental metamer also excites the melanopsin cells and the rods. Their excitation is obtained in the usual way as the integral of the product of the spectral power distribution of the colour stimulus and the action spectrum of the receptors and depends upon the chromaticity of the fundamental metamer.

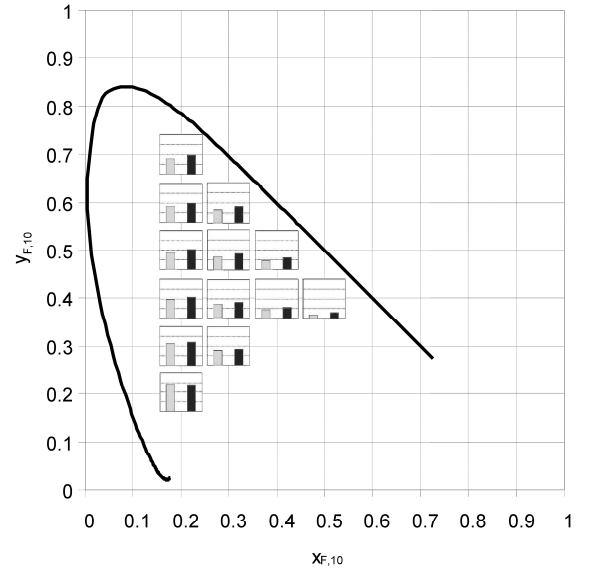


Fig. 3 Rod (dark grey bars) and ipRGC (light grey bars) excitation aroused by the fundamental metamers, at a number of chromaticity coordinates. The spectral sensitivities of the melanopsin and the rods have been normalized at peak for the calculation.

In the calculations, we have normalised the spectral sensitivities of the melanopsin and the rods at peak which gives comparable results for the two families of receptors. When the luminance is set at a fixed value $Y_{F,10} = 100$, the relative excitation of the melanopsin cells and of the rods elicited by the fundamental metamers varies over the chromaticity diagram as shown in figure 3. The variation is rather parallel for the two types of receptors, over the chromaticity diagram. The excitation is high for bluish stimuli, and very low for reddish stimuli.

4. BENEFITS FROM ADDING METAMERIC BLACKS

Our study deals with metamers designed to favour or to counteract a specific receptor response beyond cone vision. Let us recall that metameric blacks are virtual stimuli the real effect of which can be only exploited by adding their spectral power distribution to a fundamental metamer. To be feasible, the sum of the metamer components should be bounded at zero at minimum. Yet, in a theoretical study, no maximum

bound constrains the design of the spectral distribution of illumination.

A. Extension of Cohen's procedure to rod and cone metamers

The metameric blacks produced by the procedure of Cohen and Kappauf [17] are spectral distribution functions \mathbf{B} which are orthogonal to the three-dimensional colour space of human cone vision. They therefore have zero tristimulus values

$$\mathbf{A}\mathbf{B} = [0 \ 0 \ 0]^T$$

and they are invisible to human cone vision. This characteristics is obtained by using the $\mathbf{X}_{F,10}$ $\mathbf{Y}_{F,10}$ $\mathbf{Z}_{F,10}$ functions as three columns of the matrix $\mathbf{A} = [\mathbf{X}_{F,10} \ \mathbf{Y}_{F,10} \ \mathbf{Z}_{F,10}]$, see eq. (3). They will, however, excite other photosensitive retinal pigments, such as melanopsin and the rod pigment [6].

In order to study the melanopsin response alone, specific metameric blacks are required which are not only invisible to cones but also to rods. Such specific metameric blacks can be produced if the $k \times 3$ matrix \mathbf{A} is replaced by a $k \times 4$ matrix \mathbf{A}_{CR} which contains the spectral sensitivity function \mathbf{V}_{rod} of rod vision as fourth column

$$\mathbf{A}_{CR} = [\mathbf{X}_{F,10} \ \mathbf{Y}_{F,10} \ \mathbf{Z}_{F,10} \ \mathbf{V}_{rod}]$$

By using \mathbf{A}_{CR} instead of \mathbf{A} in eqs. (4) to (7), we computed metameric blacks \mathbf{B}_{CR} which had zero values in the three cone responses and in the rod response

$$\mathbf{A}_{CR}\mathbf{B}_{CR} = [0 \ 0 \ 0 \ 0]^T$$

In comparing the melanopsin response of the specific metameric blacks \mathbf{B}_{CR} with the melanopsin response of the previously used metameric blacks \mathbf{B} , we found the melanopsin response reduced by about a factor 5.

B. Differentiating the effect of metameric blacks over the chromaticity diagram

Adding a metameric black to a fundamental metamer has no effect on cone responses. It is of interest to note that adding a metameric black to the fundamental metamer may well modify the responses of the rods and of the melanopsin cells. We examined the range of excitation of the melanopsin cells and of the rods that could be achieved at a given chromaticity, by manipulating the metameric black content using the Excel solver.

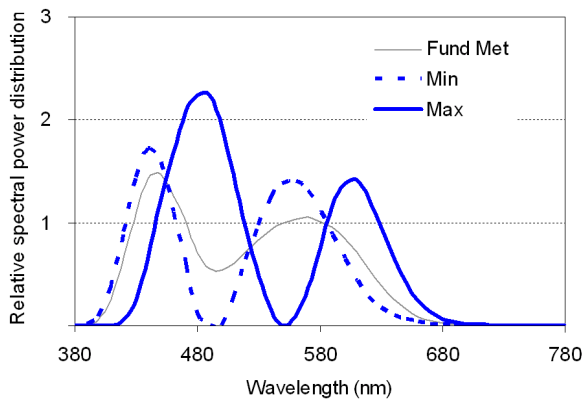


Fig. 4 (Color online) Relative spectral power distribution of the fundamental metamer for cones (thin black line) and of the same fundamental metamer to which two different metameric blacks were added that excite melanopsin and rods at maximum (thick blue line) and at minimum (broken blue line). Chromaticity coordinates $(x_{F,10}, y_{F,10}) = (0.3, 0.3)$, melanopsin excitation contrast ratio 2.19 : 1.0, rod excitation contrast ratio 1.75 : 1.0.

$y_{F,10}) = (0.3, 0.3)$, melanopsin excitation contrast ratio 2.19 : 1.0, rod excitation contrast ratio 1.75 : 1.0.

The calculation consisted in optimising the relative contribution of each spectral power distribution of the metameric blacks to maximise or minimize melanopsin excitation. Figures 4 and 5 show the optimized spectral profiles for two different sets of metameric blacks: cone metamers (Fig. 4) and metamers for cones and rods (Fig. 5). In both cases, the profile for maximum melanopsin excitation shows two peaks but the peak positions are shifted to shorter wavelengths for melanopsin-only contrast (Fig. 5). Moreover, a third peak shows up in the profile for minimum melanopsin excitation in the case of fixed rod excitation (Fig. 5, broken line). This is probably in relation with the fact that the fundamental metamer that is designed to stimulate cones, only little excites the melanopsin and rod photo-pigments.

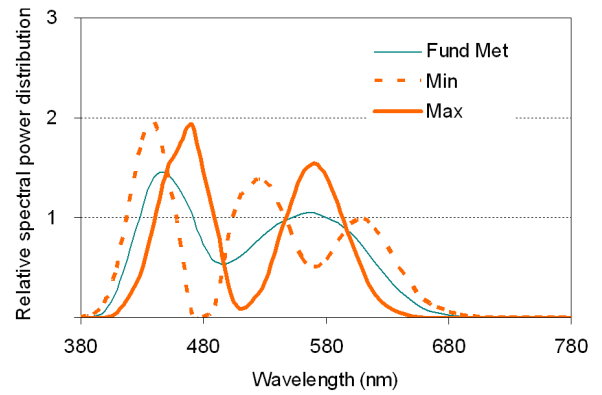


Fig. 5 (Color online) Relative spectral power distribution of the fundamental metamer for cones and rods (thin black line) and of the same fundamental metamer to which two different metameric blacks were added that excite melanopsin at maximum (thick orange line) and at minimum (broken orange line) without changing rod excitation. Chromaticity coordinates $(x_{F,10}, y_{F,10}) = (0.3, 0.3)$, melanopsin excitation contrast ratio 1.19 : 1.0.

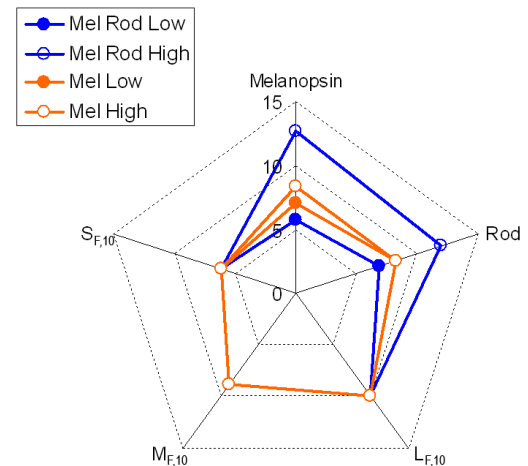


Fig. 6 (Color online) Prediction of receptor relative excitation obtained from the metamers that excite melanopsin and rods at maximum and at minimum (blue lines) and from the ones that excite melanopsin at maximum and at minimum when the rod excitation is fixed (orange).

lines), for a colour stimulus at chromaticity coordinates $(x_{F,10}, y_{F,10})$ equal to $(0.3, 0.3)$. The spectral sensitivities of all photoreceptors have been normalized at peak for the calculation.

On a radial plot, we show the excitation of the five receptor types aroused by so-derived metamers. Figure 6 shows the range of receptor excitation that is reachable for $(x_{F,10}, y_{F,10})$ chromaticity coordinates equal to $(0.3, 0.3)$. As all metamers excite the cones similarly, $L_{F,10}$, $M_{F,10}$ and $S_{F,10}$ excitation values remain the same, at a given chromaticity, whichever the metamer is. The blue lines show the maximum and the minimum excitation of rods and melanopsin cells that can be achieved when the response of both types of receptors is

allowed to vary. When only the melanopsin excitation is manipulated, the range of melanopsin excitation that can be achieved is rather limited, as shown by the orange lines.

On the full chromaticity diagram, the largest range of variation of the rods and the melanopsin cells excitation is obtained for $(x_{F,10}, y_{F,10})$ chromaticity coordinates near $(1/3, 1/3)$, which can be appreciated in Figure 7.

All results concerning the range of melanopsin excitation that could be achieved without modification of the rod stimulus were obtained using the procedure presented in paragraph 4.A.

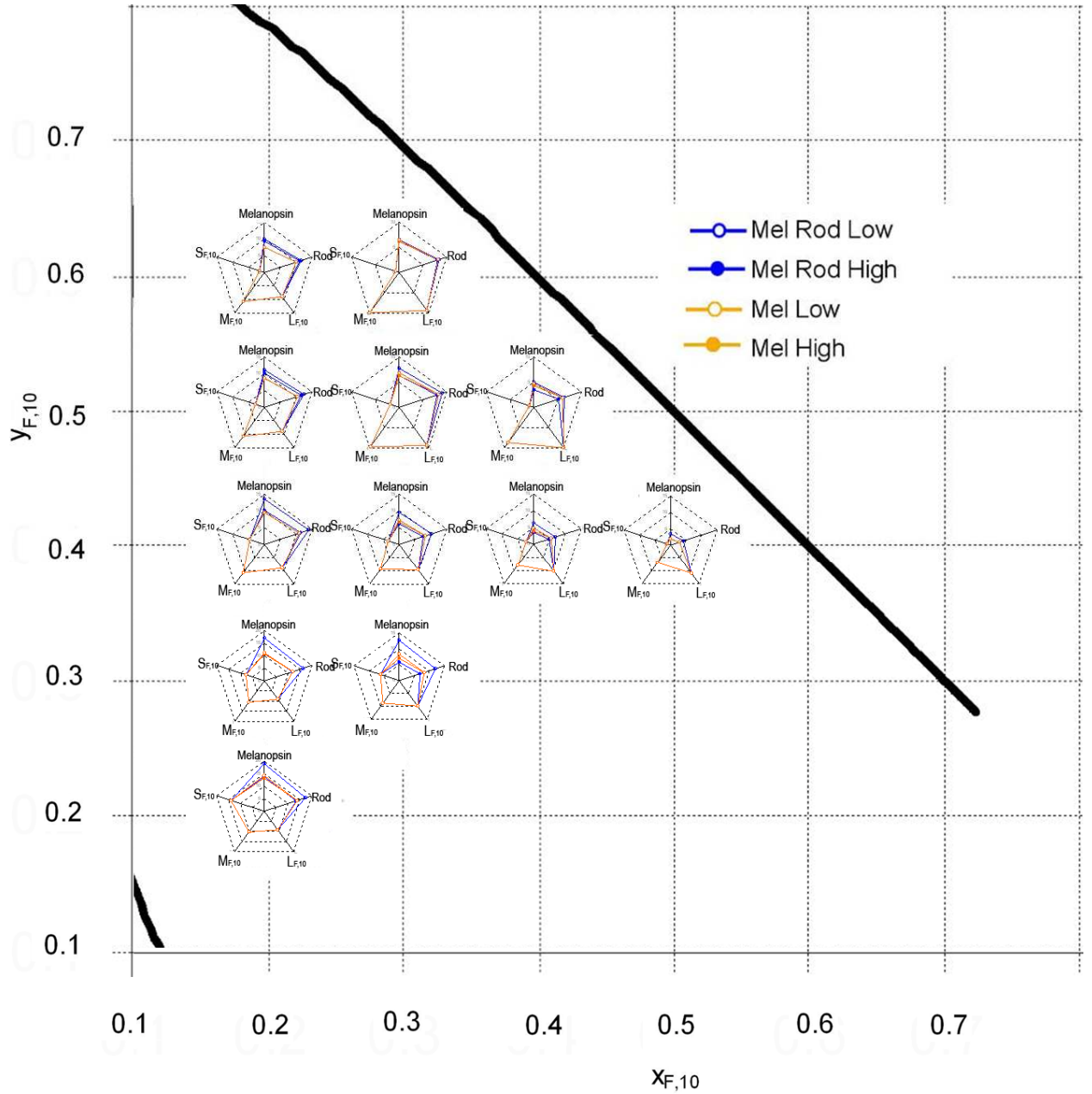


Fig. 7 (Color online) Prediction of receptor relative excitation obtained from the metamers that excite melanopsin and rods at maximum and at minimum (blue lines) and from the ones that excite melanopsin at maximum and at minimum when the rod excitation is fixed (orange lines), for a number of chromaticity coordinates.

5. DISCUSSION

A. Limitations of the receptor characteristics

Our major goal was to investigate how far the choice of illumination could isolate a photoreceptor, within a multi-receptor and multi-primary scheme. We conducted the calculation for the standard fundamental observer but we are aware that correction for the individual fundamental characteristics of each observer might be required to finely tune the metameric black spectrum. Horiguchi and colleagues have demonstrated that corrections for the individual photopigment characteristics of each observer improve fitting experimental results to a multi-receptor model including the melanopsin response [14].

Only a few studies, conducted either on cells or on physiological responses, have generated estimates of the melanopsin action spectrum. The “melanopic” spectral sensitivity function $V(\lambda)$ based on the 480 nm nomogram and derived by al Enezi et al. [38] that peaks at 488 nm, available online, is 2 nm shifted with respect to ours, while the resultant spectral sensitivity function of ipRGCs in a 10° field derived by Tsujimura et al. [13] displayed a peak wavelength of 502 nm. To curtail cone and rod responses, Gooley et al. [39] exposed a blind subject to a series of 4 min light exposures at eight different wavelengths. The pupillary constriction action spectrum was short-wavelength sensitive with a fitted peak sensitivity at 490 nm. A recent physiological study showed that the action spectrum for the calcium response in cells expressing human melanopsin had the predicted form for a vitamin A1 opsin and peaked at 479 nm [40]. Nevertheless, the exact profile of the melanopsin sensitivity is not necessary to define the metameric black base and produce metamers. An error in the determination of the melanopsin action spectrum would only propagate to the range of melanopsin contrast available at a given chromaticity.

Our results show slight differences with other studies. For our presentation we have applied a convenient normalisation to one at peak wavelength, different from the photometric normalization to 1 at 555 nm proposed by al Enezi et al. [38]. With the four primary LED system used by Brown et al. [15], the available stimuli ranged from -11% to +11% melanopsin excitation.

We did not take into account that melanopsin is a bi-stable photopigment, in the sense that it possesses two photosensitive states: photon absorption at one wavelength isomerises the 11-cis-retinal rhodopsin and initiates the phototransduction cascade while subsequent absorption at a longer wavelength isomerises all-trans-retinal back to 11-cis metarhodopsin structure to restore responsiveness [41]. The mean spike rate recorded from a macaque giant cell that expresses melanopsin increases regularly with increasing irradiance [4]. This might suggest that the equilibrium between melanopsin and metamelanopsin is only governed by the response of melanopsin. After considering situations where melanopsin responses might be influenced by a wavelength dependent pigment regeneration mechanism, Brown et al suggested the regeneration process had no effect on the action spectrum of the ipRGCs [42].

B. Choice of independent light sources

Our study rests on the fact that metamers could differently address rods and ipRGCs. To investigate this question, at least

five independent primaries are necessary. When more than five independent light sources are available, the system is over-determined and allows optimizing a solution. In a previous paper, we extended Cohen and Kappauf's procedure to white stimuli obtained from seven-color-LED mixtures [35]. The results showed that with this particular choice of seven independent narrow-band light sources, a contrast of up to 1.66 : 1.0 could be obtained in the melanopsin excitation for metameric stimuli. The question arises to which extent increasing the number of independent light sources could facilitate optimization. We therefore started a simulation of multi-LED light sources, metameric to an equi-energy light source, with more than seven independent primaries. The simulation is based on the LED model of Ohno [43] and uses multivariable search algorithms [44]. Preliminary results of this simulation show that a melanopsin excitation contrast ratio of 1.8 : 1.0 can be obtained with 8 LEDs, and a ratio of 2.6 : 1.0 with 15 LEDs.

C. Spreading the procedure to any photo-sensitive pigment

Up to now, the silent substitution method is an elegant method to independently investigate the receptor responses [45]. It has been used successfully to prepare melanopsin specific stimuli [13,14]. With the silent substitution method, the stimulus is represented in the primary space and in the receptor space and the method allows the user to maximise or minimize the receptor response. Usually, the number of primaries equals the number of receptors. In such case, the solution is unique.

All this can be accomplished using the metameric black framework. When the number of primaries exceeds the number of receptors, which is the case using many narrowly tuned spectral radiations, there are multiple combinations of primaries that can achieve silent substitution. At this point, the metameric black framework comes in and provides methods to optimize the solution, which is illustrated by the theoretical approach described in the present paper.

In previous experiments, we have already applied the metameric black framework to isolating the melanopsin response [35]. We think that the metameric black approach could be extended to any spectrally sensitive pigment. Thus, a rule could be designed to favour or to counteract a specific effect. As far as visual pigments are concerned, the \mathbf{R} matrix can be calculated from anomalous trichromat cone fundamentals. It even was in the context of studying anomalous trichromacy that Wyszecki initially presented the metameric black concept [16].

Generating cone-silent stimuli on large fields needs to take into account the spatial heterogeneity of the retina that comes out as the appearance of an entoptic colour pattern (Maxwell's spot) at the centre of the visual field. As the spatial variation of the cone fundamentals mainly originates from a variation of the optical density of the macular pigment, a crude approach consists in silencing the metamer substitution for macular pigment absorption, which cancels out Maxwell's spot or makes it appear faint.

The metameric black paradigm can be extended out of the range of visible light, once the action spectrum of the sensor to be controlled is known. Visual pigments of animals that are different from human visual pigments may be specifically addressed using the metameric black paradigm. It could be useful in studies of animal vision where a specific pigment

needs to be isolated. It could even be used outside the scope of vision, for instance to design specific light sources for skin in phototherapy. Even further, it can be applied outside the biological domain, for instance to design a harmless illumination to preserve fragile patrimonial items in a museum.

6. CONCLUSION

The metameric black concept states that any stimulus can be decomposed into a fundamental metamer that depends only on the colour specification, and a metameric black that does not affect the colour specification. The spectral power distribution of the fundamental metamer that corresponds to a collection of (x, y) values over the chromaticity diagram is shown.

The case of melanopsin receptors and/or rods is examined within a multi-primary scheme. When the luminance is set at a fixed value, we have calculated the range of excitation of the melanopsin receptors and of the rods that could be achieved at a given chromaticity, by manipulating the metameric black content.

Originally conceived to produce metameric illuminations, the metameric black concept is a powerful tool to create a colour stimulus effective on any visual photopigment besides cone photopigments using multi-primary illumination. Its application can be extended to produce illuminations that address action spectra even out the scope of vision.

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9. ENDNOTE

Note that, in [Eq. (5)].of [35], the minus one exponent sign that represents the inverse matrix operator for the middle term was accidentally omitted. Equation (5) should have been written as

$$\mathbf{R}_7 = \mathbf{A}_7 (\mathbf{A}_7' \mathbf{A}_7)^{-1} \mathbf{A}_7'$$