Towards a spatio-chromatic standard observer for detection

Sophie M. Wuerger*[a], Andrew B. Watson**[b], Albert Ahumada***[b]
[a]Communication & Neuroscience, Keele University; [b]NASA Ames Research Centre, CA

ABSTRACT

The aim of the ColorFest is to extend the original ModelFest (http://vision.arc.nasa.gov/modelfest/) experiments to build a spatio-chromatic standard observer for the detection of static coloured images. The two major issues that need to be addressed are (1) the contrast sensitivity functions for the three chromatic mechanisms and (2) how the output of these channels is combined. We measured detection thresholds for stimuli modulated along different colour directions and for a wide range of spatial frequencies. The three main directions were an achromatic direction, a nominally isoluminant red-green direction, and the tritanopic confusion line. To assess the summation across the different mechanisms 4 intermediate directions were used. These intermediate directions were the vector sums of the thresholds along the main directions. We evaluate two space-colour separable models. Both models assume that the chromatic tuning of the three mechanisms is independent of spatial frequency. Detection performance is described by a linear transformation C defining the chromatic tuning and a diagonal matrix S reflecting the sensitivity of the chromatic mechanisms for a particular spatial frequency. The output of the three chromatic mechanisms is combined according to a Minkowski metric (General Separable Model), or according to a Euclidean Distance measure (Ellipsoidal Separable Model).

1. PURPOSE

The purpose of this study is to extend the (monochromatic) threshold database and models to static coloured images. Our aim is to develop a spatio-chromatic standard observer, which will allow us to predict the visibility (at threshold) of arbitrary chromatic images. To achieve this aim we estimate the tuning of the three chromatic mechanisms, their spatial sensitivity, and the pooling factor between the chromatic channels.

2. METHODS

2.1. STIMULI

The spatial properties of the stimuli used were identical to the original ModelFest stimuli. To make the study feasible we Stimuli consisted of 12 different chromatic images, each 256x256 pixels in size. The stimuli used in this investigation was a subset of the original ModelFest stimuli and the spatial properties are described in Table 1. Each stimulus is identified by an index number. The pixel values p of each stimulus are scaled to vary from 1 to 255 and a pixel value of 128 is mapped to a contrast of 0. The pixel values p are then mapped to either chromatic, achromatic or mixed modulations around a constant mean background L_0. When a stimulus is presented at contrast c the modulation along the chosen direction L (chromatic, luminance or a mixture) is obtained by the following function:

$$L(p) = L_0\left(1 + \frac{c}{127}(p - 128)\right) \qquad (1)$$

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* s.m.wuerger@cns.keele.ac.uk; phone +44 (0)1782 584214; fax +44 (0)1782 583055; http://www.keele.ac.uk/depts/co/HMP/general/
** abwatson@mail.arc.nasa.gov
*** aahumada@mail.arc.nasa.gov

The time course of the stimulus followed a Gaussian function with a standard deviation of 0.125 seconds. The aperture was always 2 deg x 2 deg of visual angle. The background luminance and chromaticity was kept constant at 40 cd/m^2.

Index	Type	Parameters	Name
1	Gabor fixed size	1.12 c/d, sx=sy=0.5 deg	Gab#1
2	Gabor fixed size	2 c/d, sx=sy=0.5 deg	Gab#2
3	Gabor fixed size	2.83 c/d, sx=sy=0.5 deg	Gab#3
4	Gabor fixed size	4 c/d, sx=sy=0.5 deg	Gab#4
5	Gabor fixed size	5.66 c/d, sx=sy=0.5 deg	Gab#5
6	Gabor fixed size	8 c/d, sx=sy=0.5 deg	Gab#6
7	Gabor fixed size	11.3 c/d, sx=sy=0.5 deg	Gab#7
8	Gabor fixed size	16 c/d, sx=sy=0.5 deg	Gab#8
9	Gabor fixed size	22.6 c/d, sx=sy=0.5 deg	Gab#9
10	Gabor fixed size	30 c/d, sx=sy=0.5 deg	Gab#10
26	Gaussian	sx=sy=30 min	Gauss#26
35	Binary noise x Gaussian	1 min pixels, sx=sy=0.5 deg	Noise#35

Table 1: Spatial properties of stimuli. Parameters sx and sy are the horizontal and the vertical standard deviations of the Gaussian function. Only stimuli of fixed size were used based on the outcome of phase 1 of the ModelFest.

The set of stimuli used in ColorFest experiments are shown in Figure 1 below. In this example the contrast modulation is along an achromatic direction.

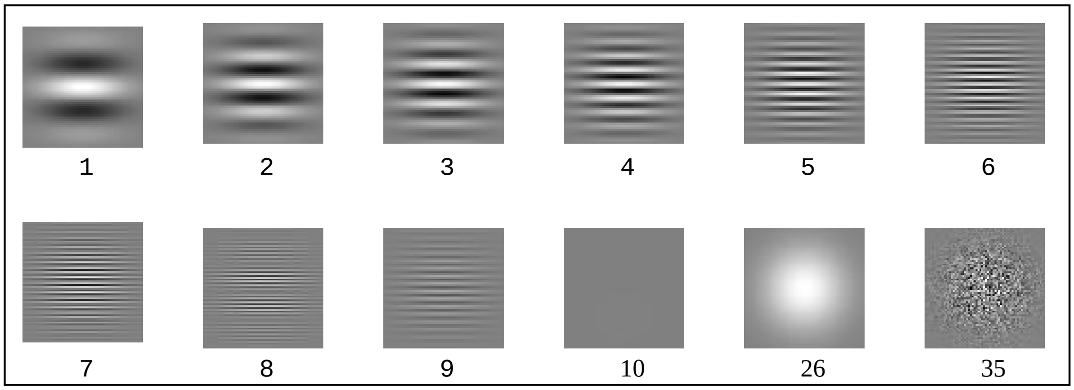

Fig. 1: ColorFest stimuli are a subset of the original ModelFest stimuli. Only the 10 Gabor Patches (#1 - #2, a Gaussian blob (#26) and noise stimulus (#35) are used. Threshold for each of these stimuli is measured in different colour directions.

2.2. COLOUR DIRECTIONS

To estimate the achromatic and the two chromatic contrast sensitivity functions (cCSF) and the summation coefficient between these three channels, three main colour directions and four intermediate directions are used. The three main colour directions were black-white (C1), reddish-greenish (C2) and yellowishgreen-violet (C3). The endoints of color directions C2 and C3 are shown in the CIE diagram (Fig. 2a). The intermediate color directions are based on threshold measurements along the three main color directions; they are the vector sum of the thresholds along the main directions. The endpoints of the two intermediate color directions (C4, C5) that lie in the isoluminant plane are shown in the Boynton-MacLeod Diagram (Fig. 2b): direction C4 varies from Purple to Green and C5 from Yellow to Blue. Color directions C6 and C7 (not shown in the graph) vary from Light Purple to Dark Green, and from Light Blue to Dark Yellow, respectively. The outside lines represent the monitor gamut for the EIZO Monitor.

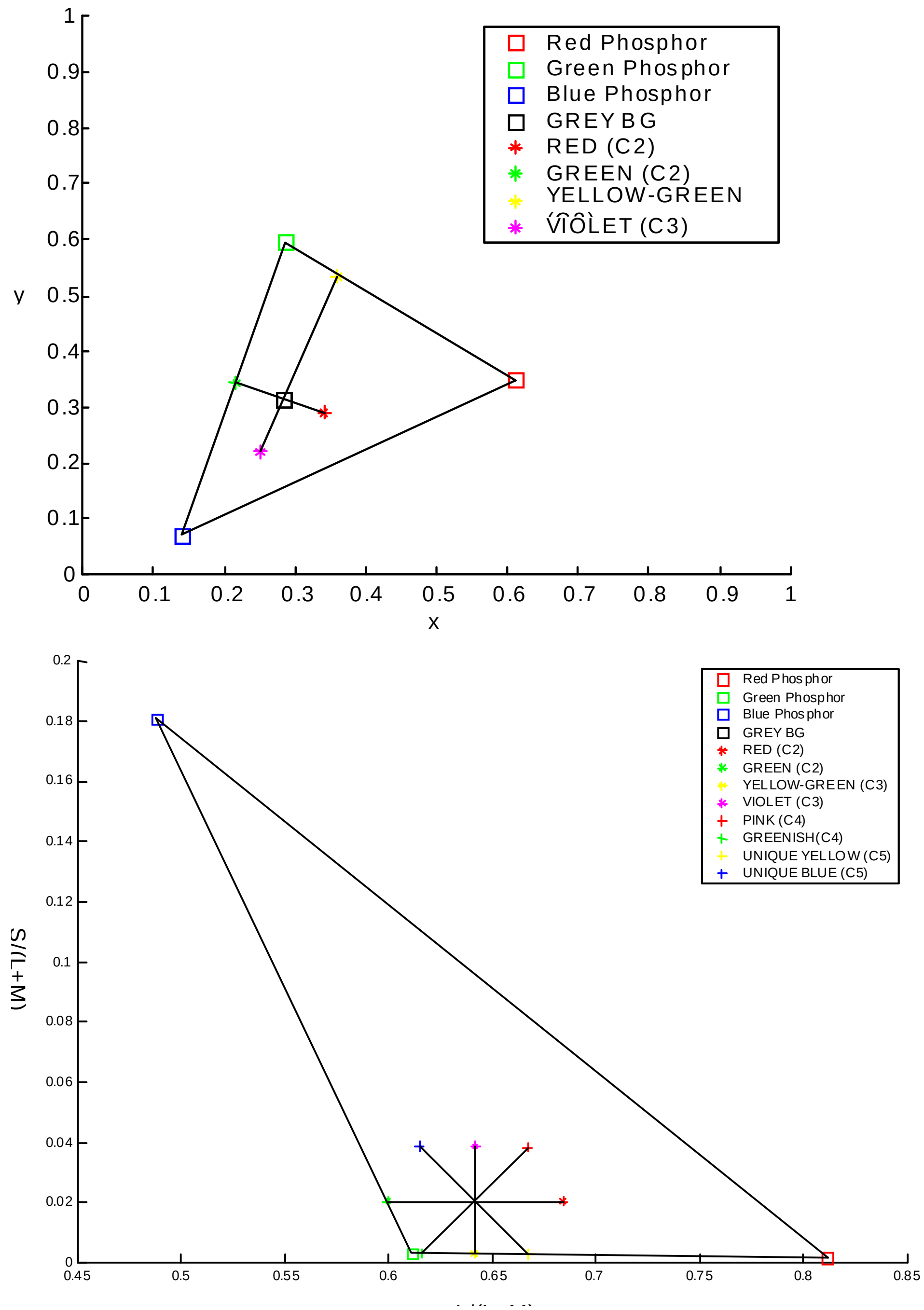

Fig. 2a: The three main colour directions in the CIE diagram. Fig 2B: The main and the intermediate colour directions plotted in the Boynton-MacLeod Diagram. The outside lines indicates the monitor gamut. The squares indicate the co-ordinates of the phosphors.

In Figure 1b. the colour directions are plotted in the L,S chromaticity diagram: the x-axis is the L cone excitation divided by the sum of the L and M cone excitations; the y-axis is the S cone excitation devided by the sum of the L and M cone excitation. The colour directions C1 to C3 are based on the V(λ) function of the CIE standard observer and on the colour matching functions estimated by Smith & Pokorny. Directions C4 and C5 were chosen such that they are on a 45 deg lines when the colour space is normalised to threshold units in the isoluminant plane spanned by the S/L+M and the L/L+M co-directions. These intermediate colour directions coincided with colours that are very close to the socalled unique hues derived from hue cancellation experiments. Colour directions C6 and C7 are chosen as the vector sums of the thresholds in the isoluminant directions and the luminance directions. Hence, modulations along these colour directions contain chromatic and luminance variations to an equal amount. The intermediate directions were chosen to provide maximum information about the summation or interaction between the three main visual mechanisms, the luminance and the three colour mechanisms. Table 2 shows the chromaticities and the endpoints of all seven colour directions. The background was always grey.

Colour Direction		Background			From Colour			To Colour		
No.	Name	L_0	M_0	S_0	ΔL	ΔM	ΔS	ΔL	ΔM	ΔS
C1	Black-White	25.88	14.42	0.83	-25.68	-14.30	-0.83	25.43	14.27	0.85
C2	Green-Red	25.88	14.42	0.83	-1.83	1.63	-0.01	1.48	-1.78	-0.01
C3	YellowGreen-Violet	25.88	14.42	0.83	-0.10	-0.00	-0.70	-0.07	-0.03	0.72
C4	Greenish-Pink	25.88	14.42	0.83	-1.07	1.07	-0.70	1.00	-1.00	0.72
C5	Yellow-Blue	25.88	14.42	0.83	1.22	-0.92	-0.01	-1.10	1.10	0.73
C6	DarkGreen-LightPink	25.88	14.42	0.83	-8.52	-3.58	-0.74	8.89	3.91	0.76
C7	DarkYellow-LightBlue	25.88	14.42	0.83	-7.01	-4.99	-0.74	7.39	5.31	0.76

Table 2: The L, M, S cone excitations of the endpoints ('From Colour', 'To Colour') of the colour directions and of the backgrounds are shown. These colour directions are plotted in Figure 2.

The main purpose of the intermediate directions was to estimate the summation across the three main colour mechanisms. Only a subset of the stimuli from Table 1 was run in these intermediate colour directions. (Table 3):

Stim No.	Gab#1	Gab#2	Gab#3	Gab#4	Gab#5	Gab#6	Gab#7	Gab#8	Gab#9	Gab#10	Gauss#26	Noise#35
Cyc/deg	1.12	2	2.8	4	5.66	8	11.3	16	22.6	30	N/A	N/A
B-W (C1)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
R-G (C2)	Y	Y	Y	Y	Y	Y	Y	-	-	-	Y	Y
YG-V (C3)	Y	Y	Y	Y	Y	Y	-	-	-	-	Y	Y
P-G (C4)	Y	-	Y	-	-	Y	-	-	-	-	-	-
Y-B (C5)	Y	-	Y	-	-	Y	-	-	-	-	-	-
LP-DG (C6)	Y	-	Y	-	-	Y	-	-	-	-	-	-
LB-DY (C7)	Y	-	Y	-	-	Y	-	-	-	-	-	-

Table 3: This table shows all the conditions run in the experiment. The intermediate directions were used to estimate the summation coefficients between the different mechanisms.

2.3. APPARATUS AND PROCEDURE

All experiments were run using a 12-bit VRG graphics card controlled by a PC. The stimuli were presented on a 17inch EIZO T561 colour monitor. The experiments were conducted in a dark room. All three observers had normal or corrected-to-normal vision. The observers viewed the stimuli with natural pupils; a chin rest was used to stabilise the observer's head. All stimuli were presented on a steady grey background. "L"-shaped corner marks were presented continuously and used as fixation guides.

Thresholds were measured using a two-interval forced-choice procedure and feedback was provided after each trial. Each threshold was measured at least three times and each threshold estimate was based on at least 32 trials. An adaptive procedure (QUEST) was used to place the stimuli and to estimate the threshold.

3. RESULTS

In figure 3, we plot the mean thresholds in decibels (dB = 20 $_{\mathrm{Log10}}$) as a function of spatial frequency for each observer. Figure 3a and 3b show the thresholds for the three main colour directions (C1,C2,C3) and the intermediate directions (C4,C5,C6,C7) , respectively. Error bars indicate plus and minus one standard deviation. To plot the thresholds as a function of spatial frequency, we need to define a one-dimensional cone contrast measure. A commonly used cone contrast measure is the vector length in cone contrast space (e.g. Brainard xxx):

$$cc = \left(\left|\frac{\Delta L}{L_0}\right|^2 + \left|\frac{\Delta M}{M_0}\right|^2 + \left|\frac{\Delta S}{S_0}\right|^2 \right)^{0.5} \Big/ \sqrt{3} \qquad (2)$$

L_0, M_0 and S_0 denote the L, M and S cone excitation of the grey adapting background and ΔL, ΔM and ΔS refer to the incremental cone excitations as shown in Table 2. For achromatic modulations this cone contrast measure is identical to the usual definition of contrast. Given our monitor gamut, the maximum cone contrasts in the three main directions can easily computed from Table 2 and are as follows: for black-white (C1): 1, for isoluminant red-green (C2): 0.08 and for the tritan line (C3): 0.49. Thus, the maximum cone contrast along an isoluminant red-green direction is not even 10% of the available contrast along the achromatic direction given the average phosphors' spectral distributions.

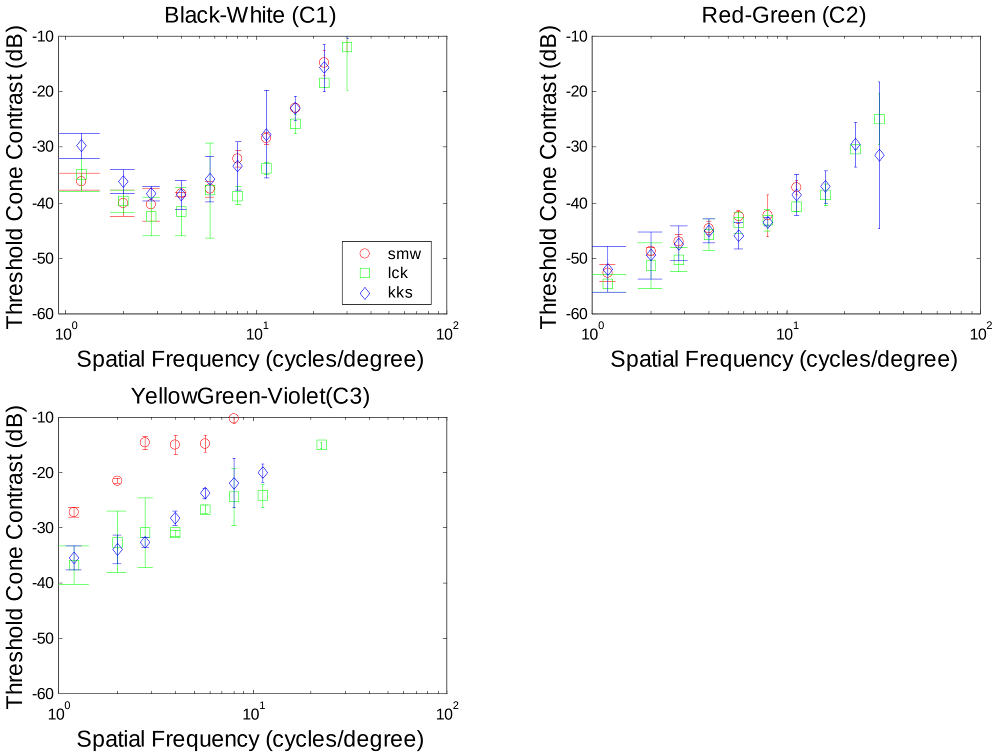

Fig. 3a: Thresholds for the three main colour directions are plotted as a function of spatial frequency for the three observers.

The thresholds for black-white modulations are replications of the previous ModelFest measurements (Watson, OSA, xxx). Our thresholds range from -45 dB for a 3cpd Gabor Patch to about -10 dB for the 30 cpd Gabor Patch, which is in very good agreement with the previous results. A comparison of the detection thresholds for modulations along the isoluminant red-green direction (C2) and the tritanopic confusion line (C3) is more difficult since the precise spatial and temporal parameters are important. To a first approximation, however, our thresholds agree quite well with the data reported by Ravamo, xxx and Dobkins, xxx. A comparison with the contrast sensitivity functions reported by Mullen, xxx, is difficult since we chose to use nominally isoluminant gratings whereas Mullen tried to control for luminance artifacts due to individual differences in the V(λ) curve and due to chromatic aberration.

Thresholds for the intermediate colour directions (C4-C7) are plotted in Figure 3b. C4 and C5 are purely chromatic modulations without any luminance components. Directions C4 and C5 are the vector sums of the thresholds along C2 and C3 and are shown in Fig. 2b. These intermediate directions were based on the average thresholds of the three observers and the same directions were used for each observer. Similarly, the intermediate directions C6 and C7 were based on the thresholds in the achromatic directions (C1) and on the thresholds in C2 and C3. C6 and C7 are not shown in Figure 2b. The maximum available cone contrasts in these intermediate directions are as follows: 0.49 for C4, 0.49 for C5, 0.57 for C6 and 0.58 for C7.

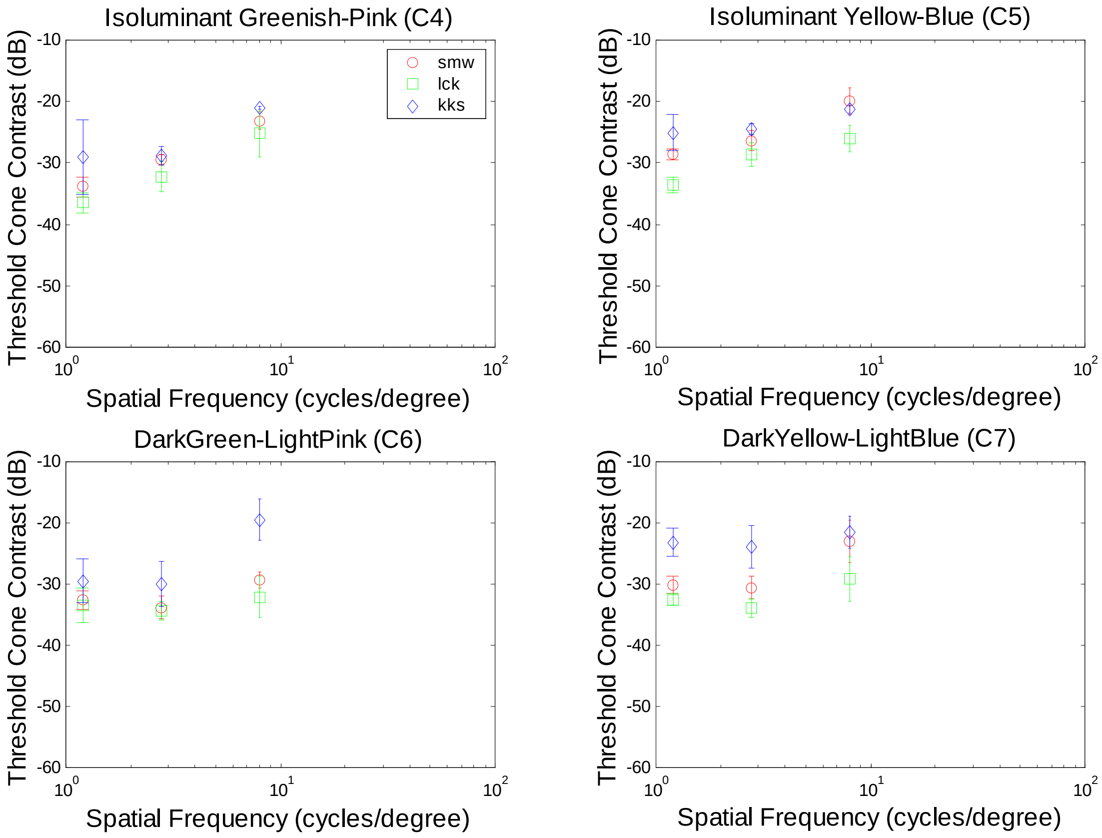

Fig. 3b: Thresholds for the four intermediate colour directions are plotted as a function of spatial frequency for the three observers.

4. MODELS

The aim is to derive contrast sensitivity functions for the three main colour mechanisms and to assess how the information is pooled across these colour channels. We consider two different classes models (cf. Poirson & Wandell, 19xx): models that assume that the spatial sensitivity is independent of the chromatic tuning (space-colour separable models), and models that to not assume this separability of spatial and chromatic sensitivity.

4.1. GENERAL STRUCTURE

We consider several different models. All models consist of four general stages: (1) conversion from absolute cone excitations to cone contrast in each of the three cone classes, (2) linear re-combining of the cone contrast signals into chromatic mechanisms, (3) spatial filtering of the output of each of the three chromatic mechanisms, and (4) pooling across the filtered chromatic output.

Step 1: Conversion to L,M,S Cone Contrast

$$c_L = \frac{\Delta L}{L_0}; \quad c_M = \frac{\Delta M}{M_0}; \quad c_S = \frac{\Delta S}{S_0} \qquad (3)$$

where L_0, M_0 and S_0 denote the L, M and S cone excitation of the grey adapting background and ΔL, ΔM and ΔS refer to the incremental (or decremental) cone excitations of the stimulus. Each chromatic stimulus of a particular spatial frequency f is then defined as

$$\mathbf{x_f} = \begin{bmatrix} c_L \\ c_M \\ c_S \end{bmatrix}_f \qquad (4)$$

Step 2: Linear Re-combination of the L,M,S cone contrasts into new colour functions

The cone contrasts are linearly re-combined into three new mechanisms:

$$\begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} m_{1L} & m_{1M} & m_{1S} \\ m_{2L} & m_{2M} & m_{2S} \\ m_{3L} & m_{3M} & m_{3S} \end{bmatrix} \begin{bmatrix} c_L \\ c_M \\ c_S \end{bmatrix} \qquad (5)$$

or equivalently,

$$\begin{bmatrix} \\ \mathbf{M} \\ \\ \end{bmatrix} = \begin{bmatrix} & & \\ & \mathbf{C} & \\ & & \end{bmatrix} \begin{bmatrix} \\ \mathbf{x} \\ \\ \end{bmatrix} \qquad (6)$$

where **M** denotes the output of the three new mechanisms, and **C** is the colour matrix that maps the L,M,S cone contrasts into the new mechanisms M_1,M_2 and M_3.

Step 3: Spatial Scaling of the output of the three colour functions (M_1,M_2 and M_3.)

After the mapping into the new colour functions, the colour signals are scaled according to the spatial sensitivity of the particular colour mechanism. We assume that there is no interaction between the three colour mechanisms. We denote the scaled output of the three colour functions at a particular spatial frequency f with $\mathbf{R_f}$:

$$\begin{bmatrix} R_1 \\ R_2 \\ R_3 \end{bmatrix}_f = \begin{bmatrix} s_1 & 0 & 0 \\ 0 & s_2 & 0 \\ 0 & 0 & s_3 \end{bmatrix}_f \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix}_f \qquad (7)$$

or equivalently,

$$\begin{bmatrix} \\ \mathbf{R}_f \\ \\ \end{bmatrix} = \begin{bmatrix} \mathrm{O} & & \\ & \mathbf{S}_f & \\ & & \mathrm{O} \end{bmatrix} \begin{bmatrix} \\ \mathbf{M}_f \\ \\ \end{bmatrix} \qquad (8)$$

The matrix **S** is a function of spatial frequency and the three scaling factors (s_1, s_2 and s_3) are estimated for each spatial frequency. **M** are the outputs of the three colour mechanisms.

Step 4: Pooling over the scaled output of the three colour functions (R_1, R_2 and R_3.)

The final step is the pooling of the scaled colour responses using a Minkowski metric,

$$r_f = \left[\sum_{i=1}^{3} \left| R_{if} \right|^{\beta} \right]^{1/\beta} \qquad (9)$$

where r_f is the single-valued output for a particular spatial frequency, R_{if} is the scaled output of colour mechanism i, and β is the pooling exponent across the colour mechanisms.

Hence the response of the visual system (r_f) to a chromatic stimulus of spatial frequency f may be written as follows:

$$r_f = \left[\left(\left| \mathbf{S}_f \ \mathbf{C}\,\mathbf{x}_f \right|^{\beta/2} \right) \left(\left| \mathbf{S}_f \ \mathbf{C}\,\mathbf{x}_f \right|^{\beta/2} \right)^T \right]^{1/\beta} \qquad (10)$$

where $\mathbf{x_f}$ is 3x1 vector containing the L,M,S co-ordinates of a stimulus of a certain spatial frequency; **C** is a 3x3 matrix where row i contains the L,M,S weights for mechanism i; matrix **C** maps the L,M,S cone contrasts into the new colour function responses. $\mathbf{S}_f$ is a 3x3 diagonal matrix that defines the spatial sensitivity for each of the three colour direction at a particular spatial frequency f and β is the pooling exponent across the three chromatic mechanisms.

4.2. SPECIFIC MODELS

There are two major classes of models: space-colour separable models (c.f. Poirson and Wandell) and non-separable models. Space-colour separable models are models where the matrix (C) that defines the chromatic tuning is independent of the spatial frequency. The model described in equation (10) is separable if the matrix C is estimated independently of the spatial frequency. We call models inseparable, if the chromatic tuning depends on the spatial frequency. Equation (10) defines an inseparable model if matrix C is different for each spatial frequency. Here we only consider space-colour separable models. Table 4 below describes the main features of the models. More details about the parameters are given in the following sections.

Model	Spatial Sensitivity (S)	Colour Tuning (C)	Pooling Exponent (β)	Free Param.
General separable model (GSMa):	Constrained (10)	Free to vary (9)	Free to vary (1)	21
General separable model (GSMb):	Constrained (10)	Constrained (9)	Free to vary (1)	21
General separable model (GSMc):	Constrained (10)	Fixed (0)	Free to vary (1)	12
Ellipsoidal separable model (ESMa):	Constrained (10)	Free to vary (9)	2 (0)	20
Ellipsoidal separable model (ESMb):	Constrained (10)	Constrained (9)	2 (0)	20
Ellipsoidal separable model (ESMc),:	Constrained (10)	Fixed (0)	2 (0)	11

Table 4. This table shows the free parameters of the general and the ellipsoidal models. For all models, the spatial sensitivity parameters are constrained. The L,M,S cone weights of the colour functions are free to vary in models 1a and 1b and are fixed in models 3a and 3b. The number of free parameters are shown in parentheses in each column. The total number of free parameters includes an additional constant (Eq 12 below) and is shown in the last column.

4.2.1. Chromatic Tuning

In Models 1a,b and 2a,b the 9 coefficients of colour matrix C are estimated. In Models 1c and 2c the chromatic tuning (C) is not estimated from the data but specific colour mechanisms are assumed. We used the following colour mechanisms (cf. Derrington et al., ???): a luminance mechanism, an L-M mechanism and a mechanism that takes the difference between the sum of the L and M cones and the S cones. The matrix C was chosen such that the three mechanisms produce unit outputs for stimuli of unit strength along the three main chromatic modulations (C1-C3, cf. Table 2). Stimuli of unit strength were arbitrarily defined as stimuli with the same vector length in cone contrast space (Eq. 2). Hence the colour matrix C is the inverse of the stimulus matrix:

$$C = \begin{bmatrix} 1.11 & 0.62 & 0 \\ 0.74 & -0.74 & 0 \\ -0.64 & -0.36 & 1 \end{bmatrix} \qquad (11)$$

The first row defines the L, M and S cone input to the luminance mechanism. The second row is L, M, S cone weighting the red-green mechanism, and the third row is a mechanism that takes the difference between the S and the (L+M) cone input.

In Models 1b and 2b the chromatic mechanisms (matrix C) are constrained in that the signs of the coefficients are fixed. Hence we obtain a mechanism that sums the L and M cones, a mechanism that takes the difference between the L and M cones, and a third mechanism that takes the difference between the S cones and the sum of the L and M cones.

4.2.2. Spatial Sensitivity

In all models, the spatial sensitivity (S) is constrained. We always fit three contrast sensitivity functions: a typical 'bandpass' function for one mechanism (Tyler's model, cf. Watson, 19xx, 4 free parameters) and Gaussian functions for the other two mechanisms (3 free parameters for each function: mean, sigma, amplitude). For each model we thus estimate 10 parameters that characterise the spatial sensitivity of the colour functions.

4.2.3. Pooling across the chromatic mechanisms

In models 1a,b,c the pooling exponent (Eq. 9) is a free parameters, in models 2a,b,c we set the pooling exponent to 2. A pooling exponent of 2 is identical to a vector length model, i.e. the vector length of the three chromatic outputs is computed.

4.3. (PRELIMINARY) MODEL FITS

To fit these models to our data, we assume that the probability of detection is proportional to the output of the visual system $r_{f.}$ (Eq 10). Hence we set r_f to an arbitrary constant (*const*). For each observer and for each model, we minimise the average squared deviations between the output given the model and the (arbitrary) criterion value of 1.

$$MeanSquaredError = \frac{1}{N} \sum_{i=1}^{NF} \sum_{j=1}^{NC(i)} \left(1 - const * \bar{r}_{ij}\right)^2 \quad (12)$$

where $\bar{r}_{ij}$ denotes the mean response to a stimulus of spatial frequency *i* and a colour modulation *j*. The mean squared error is computed over all spatial frequencies NF and all colour directions NC. N is the total number of data points. The mean response is the average over all replications K at frequency *i* and colour modulation *j* and defined as follows:

$$\bar{r}_{ij} = \frac{1}{K} \sum_{k=1}^{K} r_{ijk} \quad (13)$$

Table 4 shows the mean squared deviations for all models. GSM are the general separable models, ESM are the ellipsoidal separable models. The difference between these two models is that the pooling exponent is a free parameter in the general separable models and is set to 2 for the ellipsoidal models. For the ellipsoidal models Eq. 9 defines the Euclidean distance and the total response is the vector length of the chromatic responses.

Model No. free parameters	GSMa 21	GSMb 21	GSMc 12	ESMa 20	ESMb 20	ESMc 11
KKS	0.0800 (35)	0.0749 (35)	0.4195 (35)	0.1408 (35)	0.2073 (35)	0.6100 (35)
LCK	0.0652 (35)	0.0926 (35)	0.3611 (35)	0.1513 (35)	0.3626 (35)	0.4828 (35)
SMW	0.0422 (35)	0.0969 (35)	0.3194 (35)	0.1632 (35)	0.2982 (35)	0.4701 (35)
ALL	0.1989 (105)	0.1999 (105)	0.4127 (105)	0.3873 (105)	0.5339 (105)	0.6837 (105)

Table 4. Mean squared deviations are shown for each model and for all observers. The number of data points is given in parentheses. The last row contains the mean squared deviations when all observers are fitted simultaneously.

Figure 4 shows two examples of estimated contrast sensitivity functions ($\mathbf{S_f}$) for the three colour functions (M1,M2,M3) for two models. (a). Contrast sensitivity functions for the Ellipsoidal Model with unconstrained colour functions and a pooling exponent fixed at 2 (ESMa). (b) CSFs for the Ellipsoidal Model with fixed colour functions and a pooling exponent fixed at 2 (ESMc). The models were fitted for all observers simultaneously. The contrast sensitivity functions were constrained for both models: one CSF was always a 'bandpass' filter, for the other two CSFs Gaussian functions were fitted with 3 free parameters each (mu, sigma, amplitude).

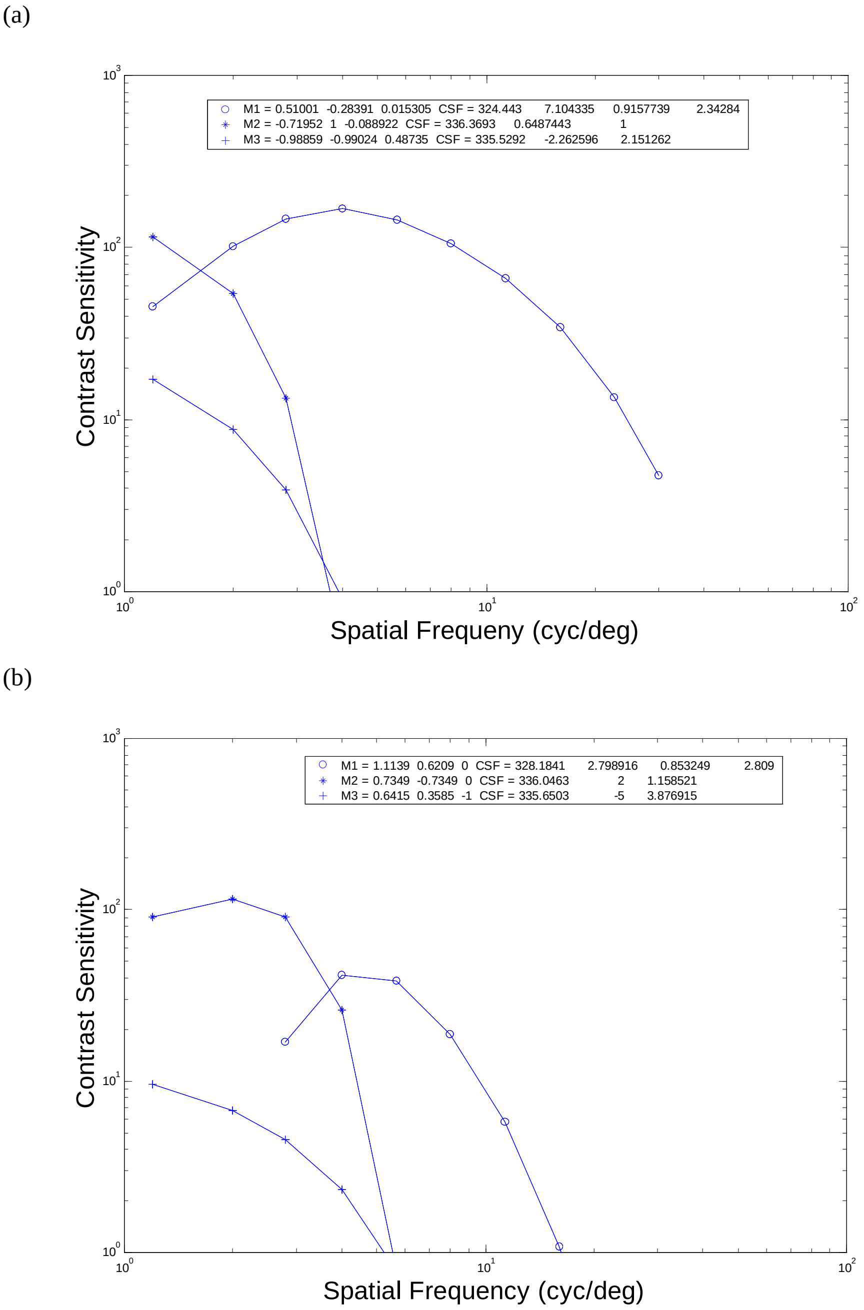

Fig. 4. Figure 4 shows two examples of estimated contrast sensitivity functions (a). Contrast sensitivity functions for the Ellipsoidal Model with unconstrained colour functions and a pooling exponent fixed at 2 (ESMa). (b) CSFs for the Ellipsoidal Model with fixed colour functions and a pooling exponent fixed at 2 (ESMc). The models were fitted for all observers simultaneously.

5. CONCLUSIONS

The aims of the ColorFest are to build a spatio-chromatic standard observer and to generate a database of chromatic detection thresholds that can be used by the scientific community to evaluate their models. This present paper is a first attempt to extend the previous ModelFest experiments and models to static chromatic images.

From this pilot study we conclude the following:

(i) Our detection data for achromatic stimuli are in good agreement with the measurements obtained in Phase I of ModelFest (Fig. 3a; cf. Watson, 19xx). Using nominally isoluminant stimuli (based on the CIE standard observer) will not allow us to isolate the putative red-green chromatic mechanisms. Fig 3b indicates that the detection of higher spatial frequencies is probably mediated by a luminance mechanism rather than a red-green mechanism. Similarly, the detection for stimuli along the tritanopic confusion line (Fig. 3c) of medium spatial frequency seems to be mediated not by the yellowish-violet mechanism. This is particularly clear for one observer.

(ii) The goodness of fit of the models is greatly improved by estimating the L,M,S weights of the colour functions, instead of using the commonly used colour functions (cf. Table 4). Allowing the pooling exponent to vary freely (instead of setting it to 2) does not greatly improve the quality of the fits.

The ColorFest group needs to make decisions about the following issues:

(i) The choice of the colour modulations, i.e. whether we want to base the chromatic modulations of the stimuli on the CIE standard observer or on individual measurements

(ii) The choice of the spatial frequencies to be used in the ColorFest experiments.

(iii) The kind of models we want to test and how we compare the goodness of fit of these models

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