Abstract

A metameric colour matching test was designed to study inter-observer variability. Blue-yellow metameric matching to a white-light continuum was used to define the optimal wavelengths at which each of eight non-colour-defective observers achieved a match. The tests involved chromatic stimuli on a 2º bipartite field, with a white-light continuum presented on the left half, and a mixture of two monochromatic stimuli on the right half. The luminance of these chromatic stimuli was adjusted by the researcher using a staircase method, with the observer providing feedback about the similarity in luminance and chromaticity between the two halves of the field. Two series were performed for each observer, using different fixed yellow wavelengths. Since for each fixed yellow wavelength the match with the target white can be achieved by only one

corresponding blue wavelength which is particular for each observer, the initial blue wavelengths were approximations based on the 2º CIE 1931 standard observer. Once the observers had attained an achromatic match, they modified the blue wavelength to achieve a perfect match of both halves. Generally, the observers found this modification of the blue wavelength necessary to achieve the metameric match. Each observer had a particular optimal blue wavelength which differed between the two series. The differences between the deviations from the standard observer for the two series were constant in value among the observers.

Keywords

blue-yellow channel, colour vision, complementary colour stimuli, individual differences, metameric match

Introduction

The primary objective of systems that manage colour reproduction is fidelity of the reproduction, i.e. the same visual appearance of the colours displayed on different devices that are capable of producing chromatic stimuli, even when those devices use different sets of primary stimuli. The possibility of achieving this objective is based on humans' ability to perceive as equal two chromatic stimuli with different spectral distributions of radiant power but identical tristimulus values. In colorimetry this is known as metamerism (Wyszecki and Stiles, 1982).

Since tristimulus values are a result of the interaction between a physical stimulus and the human visual system, there are two types of metamerism: illuminant metamerism (CIE, 2004) for a fixed observer but with two different light sources illuminating the same sample, and observer metamerism (CIE, 1989) for a fixed light source and two different observers.

Phenomenologically, every observer is characterized chromatically by colour matching functions (CMFs). These indicate the amount of each primary needed in a mixture to achieve a match. There are small differences in these amounts between normal observers, with extreme cases of large differences corresponding to defective observers. These differences are especially perceptible in certain types of colorimetric matching of spectral stimuli. Examples are Rayleigh matching used extensively to detect red/green deficiencies; Engelking-Trendelenburg and Moreland matching to detect blue/yellow deficiencies; and Pickford-Lakowski matching to study the effect of age on colour vision (Working Group 41, 1981; Engelking, 1925; Trendelenburg, 1941; Moreland and Kerr, 1978; Moreland, 1984; Moreland and Roth, 1987; Lakowski, 1971; Roth, 1984).

In all of these techniques, the wavelengths of the spectral stimuli used in the mixture are kept fixed, and only the ratio of the mixture or the intensity of the reference is varied.

In recent years, the international scientific community has been making an effort to relate the differences between individuals that are manifest in metameric matching (Diaz Navas et al., 1998; Thomas and Mollon, 2004; Vienot et al., 2006) to variations in such physiological factors as the optical densities of the intraocular media (Webster and MacLeod, 1988); the long (L-) to medium (M-) wavelength sensitive cone photopigments (Stockman and Sharpe, 2000); the cone ratio (Brainard et al., 2000), etc. These physiological factors are known to be largely responsible for inter- observer differences.

In its recent publication, the CIE (2007) specified a method for generating the fundamental response curves of each individual observer given the values of the maximum sensitivity wavelengths for each type of photopigment and of the optical densities of the intraocular media, the macular pigment, and the photopigments.

The aim of the present work is to contribute to the determination of each individual observer's fundamental response curves by developing a method to determine the individual differences among several observers and their correlation with some of the physiological variables alluded to above. Specifically, using two blue-yellow metameric matches of a white-light continuum in eight non-colour-defective observers, we aim to define the optimal wavelengths at which each observer achieved the match. We want to show the intra-observer difference (the difference in wavelength of the blue spectral stimuli chosen to match with the two yellow spectral stimuli), and interobserver differences. With these matches, we obtain two complementary monochromatic pairs for each of these observers given a single continuous white reference.

Methods

Three techniques have been widely used to measure the detection, discrimination and subjective estimation of a stimulus: absolute threshold detection, differential threshold determination and scale elaboration (Gescheider, 1997). The techniques we use do not fit the differential threshold determination category, although the observers implicitly make use of their discrimination threshold when they acknowledge a match as valid using a staircase method. Neither can we strictly speaking classify them as a scale test, as the observer does not subjectively estimate any of the perceptual attributes between several visual stimuli. Instead we designed the tests to be midway between these two categories in order to reduce the effort that the (normally voluntary) observer has to make in forming a subjective estimate of various chromatic stimuli. Since several objections have arisen on the comparison of juxtaposed stimuli in a bipartite field, in which the observer merely responds whether or not the match is good, we asked the observer to give more details about the perceptual attribute being tested.

Experimental set-up

We used central foveal monocular vision with a natural pupil, with a pseudo-Maxwellian observation method due to the characteristics of the equipment (Figure 1) that uses a lens instead of an integrating sphere to display the field to the observer. The stimuli were presented to the observer on a 2º bipartite field surrounded by a 15º adaptation field onto which an achromatic stimulus with a constant luminance of 28 cd m^{-2} was projected with high incidence angle to avoid reflection from the lens. Both the central field size, <4º, and the luminance level of the surrounding field, ensure that the contribution of the rods to any match is negligible or zero.

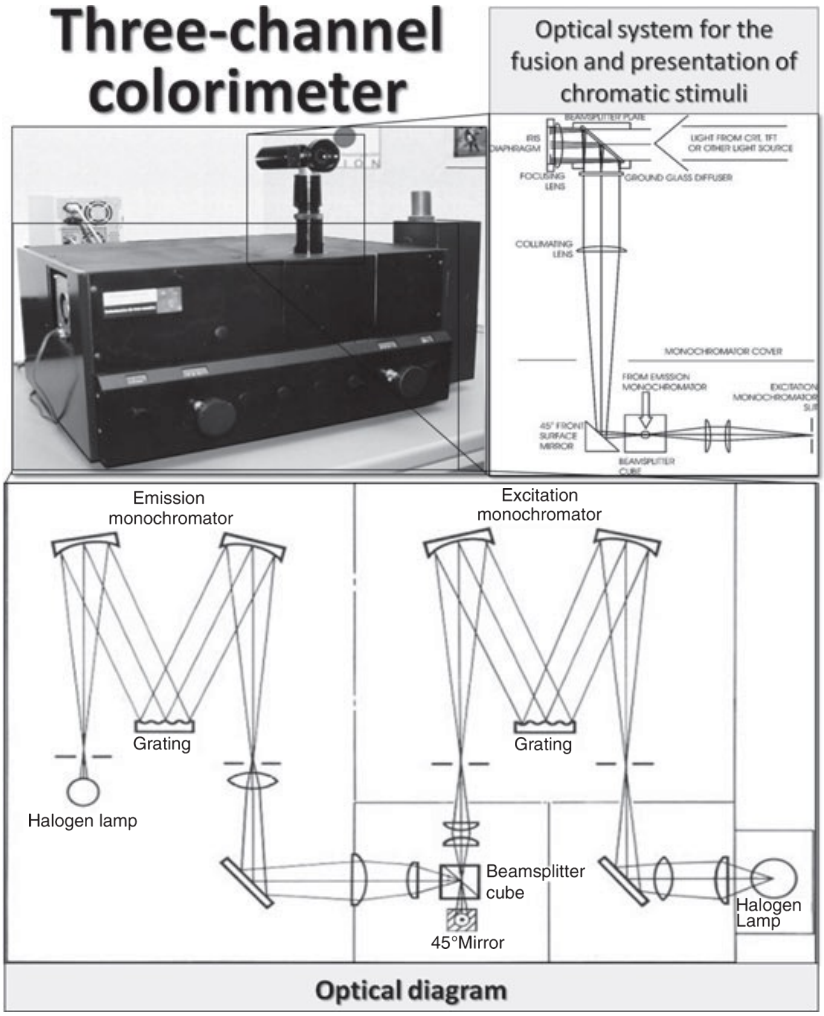

Figure 1. Optical system of the three-channel visual colorimeter equipped with two monochromators with a Czerny-Turner mount holding a 1200 grooves per mm grating and a third free configurable channel.

The observers used a chin and forehead support, and a cross-shaped mark was used to ensure that they fixed their eyes on the same spot. The equipment was located in a dark room in order to control lighting conditions.

A white-light continuum from an 8 W fluorescent light was presented on the left half of the 2º field, matching the adaptation field in luminance. A mixture of two monochromatic stimuli was presented on the right half of the field: a 484 nm blue and 576 nm yellow in the first series, and a 492 nm blue and 592 nm yellow in the second series, with a FWHM of 10 nm (see Figure 2).

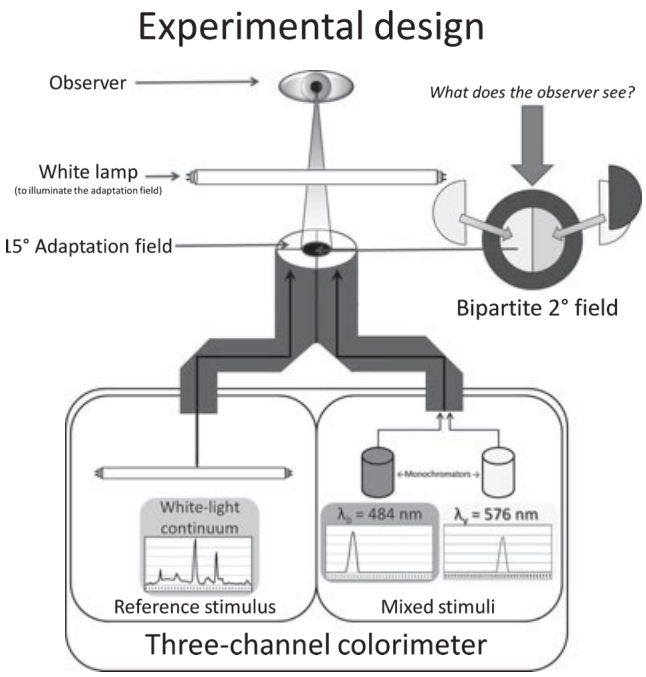

Figure 2. Schematic illustration of the metameric matching procedure.

To properly conduct a psychophysics experiment, one needs a system to supply accurate chromatic stimuli. The colour generating system used in the present work was a new visual three-channel colorimeter, constructed by the authors by recycling an old fluorescence spectrophotometer with two monochromators (Pardo et al., 2004a). The optical system was designed to allow the fusion of two visual stimuli coming from two monochromators of the spectrofluorimeter. Two 100 W halogen lamps were used as light sources for the monochromators. Using halogen incandescent lamps enables the luminance to be regulated by varying its voltage by means of two independent, voltage-stabilized, power supplies. This form of regulating the intensity (luminance) of the lamps has the drawback that it modifies the emission spectra. However, this problem was solved with a neural network based calibration system that takes this effect into account and provides very good results (Pardo et al., 2004b). The two spectral light beams meet at a 90º angle at the point where the samples were usually located in the spectrofluorimeter, and are presented to the observer on the right half of a 2º visual field.

A PR-701 spectroradiometer (Photo Research Inc., Chatsworth, CA, USA) with 2 nm resolution and luminance sensitivity of 0.003 cd m^{-2} was used to determine the proper working wavelengths, and to calibrate the devices.

Observers

The sample population consisted of eight observers, all characterized as chromatically normal using the Ishihara 38-plate test, the Farnsworth-Munsell D-15 test, and anomaloscopic tests. Their ages were between 25 and 35 years: this was to eliminate as far as possible the influence of age on metameric matching, in which the short wavelengths are especially involved due to the well-known effect of ageing on the intraocular media (Webster and MacLeod, 1988).

The observers had previously been trained to become accustomed to the experimental set-up. Every experimental session began with 5 min adaptation to the dark-room lighting conditions, and the observer was placed in front of the white adaptation field.

No time was set for the exposure to the chromatic stimuli so as to produce observations that were as natural as possible, with a stable cone response. Nonetheless, a chopper forced the observers to re-accommodate their vision to the observation field every 30 s. Each match was repeated five times for each observer.

Procedure

Two blue-yellow metameric matches to a white-light continuum were performed, seeking to determine the optimal short wavelength at which each match was achieved given the fixed wavelength of the yellow com- ponent. These matches, closely related to the type known as Pickford-Lakowski (Pokorny and Smith, 1986), are more difficult to obtain than those from a classic Rayleigh match of a monochromatic yellow using two

monochromatic red and green stimuli, because for any given fixed yellow to match a particular spectral white, there is only one suitable blue wavelength. One can simulate these matches using the CMFs of the 2º CIE 1931 standard observer, taking as a starting point the spectral power distribution of the white-light continuum. The tristimulus values generated by this white light must be equal to the tristimulus values of the sum of two spectral stimuli – one of a fixed wavelength of 576 nm and the other of a variable wavelength – chosen in suitable proportions. Using an iterative algorithm to determine the error in the tristimulus values for all combinations of the energy of the two peaks and of the wavelength of the blue stimulus, one observes a single point of minimum difference between the tristimulus values of the right and the left halves of the field (Figure 3).

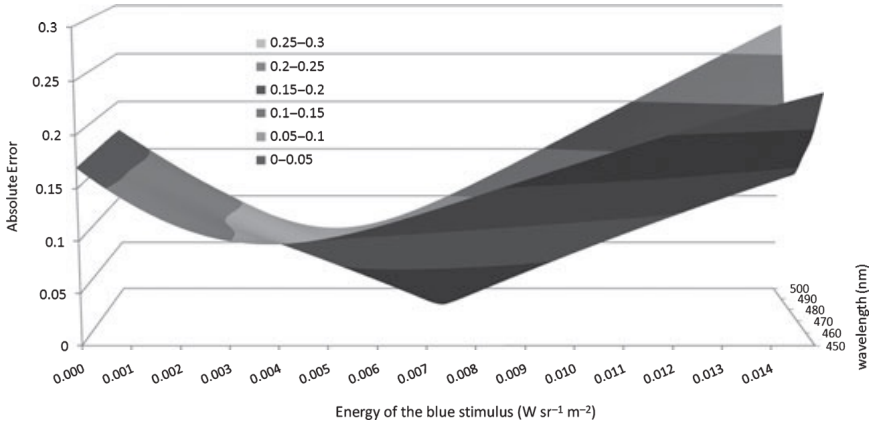

Figure 3. The error obtained in the mathematical simulation of one of the matches vs variations in wavelength and energy in the blue stimulus for a fixed energy value of the yellow stimulus.

There is an extra difficulty in that this wavelength is observer-specific. To verify this point, we simulated the same matches using as the mathematical model the 10 colour matching function triplets obtained by Stiles and Burch (1955) for 2º fields (retrieved from the website of the Colour & Vision Research Laboratory at the Institute of Ophthalmology of University College Lon- don at http://www.cvrl.org). An algorithm

was implemented in Visual Basic for Excel that ran through all the energy combinations of the two yellow and blue spectral stimuli, also covering the 450–500 nm wavelength range for the blue. We obtained the energy values of both spectral peaks plus the wavelength of the blue spectral stimulus that yielded the minimum error in each match. These values are listed in Table 1. They range between 10 and 7.5 nm, with a mean for the 10 observers of 8.5 nm.

Table 1. The two blue wavelengths and their difference obtained from the colour matching functions of Stiles and Burch (1955) for 2° fields (10 individual observers and average for the 10 observers).

Obs	1	2	3	4	5	6	7	8	9	10	Avg
k_1 (nm)	481.5	482.5	482.5	482.0	477.5	485.0	481.0	481.5	484.0	482.5	481.5
k_2 (nm)	491.0	490.5	490.5	488.5	487.0	492.5	489.5	491.5	491.5	490.5	490.0
Dk (nm)	9.5	8.0	8.0	6.5	9.5	7.5	8.5	10.0	7.5	8.0	8.5

The observers in the experiment could modify the blue wavelength precisely by means of a gear lever which regulates the colorimeter's blue channel diffraction grating, with the yellow wavelength being fixed to simplify the calculations. This was implemented by first asking the observers to reach a match which was as achromatic as possible, and then asking them to modify the blue wavelength to achieve a perfect match of both fields. A first matching procedure took as initial wavelengths 484 and 576 nm, and this was followed by a second procedure taking as initial wavelengths 492 and 592 nm.

Results

Generally, the observers found it necessary to modify the blue wavelength to achieve the metameric match. Each observer had a particular optimal blue wavelength in each of the two series and different energy ratios K too (Table 2).

Table 2. Wavelengths and energy ratios at which the different observers found a match.

	Obs. 1		Obs. 2		Obs. 3		Obs. 4		Obs. 5		Obs. 6		Obs. 7		Obs. 8	
k_{yellow} (nm)	576	592	576	592	576	592	576	592	576	592	576	592	576	592	576	592
k_{blue} (nm)	478	486	485	493	480	488	482	490	481	488	479	487	477	485	482	490
K	1.15	1.94	1.46	2.56	1.12	2.00	1.27	1.61	1.24	1.66	1.18	1.69	1.10	1.72	1.36	1.87
r_K	0.03	0.03	0.03	0.05	0.03	0.07	0.03	0.03	0.03	0.04	0.03	0.04	0.04	0.03	0.02	0.06

The measuring instrument's spectral resolution (2 nm) limits the precision of these wavelength measurements to an error that in no case can be less than ±1 nm; nevertheless all the observers showed a null variance for the five matches with a monochromator wavelength step of 0.5 nm. With respect to the ratio of the blue/yellow mixture, the table lists the values of the radiant flux ratios and the corresponding standard error. In general, the values of the variance were low, and there was little scatter in the data.

The different blue spectral wavelengths chosen by the observers show inter-individual differences. One notes, however, that in almost all the observers (seven out of eight) there was the same distance (8 nm) between the blue spectral stimuli chosen in the two matches.

Discussion

The measurements of the optimal wavelengths at which each observer achieved two different blue-yellow metameric matches of a given white-light continuum showed that these wavelengths differed between observers.

These differences in the choice of the optimum wavelength for full metameric matching may be due to individual differences in such physiological variables as the macular pigment optical density, yellowing of the lens, the wavelength of maximum sensitivity of the L and/or M cone photopigments, and the photopigment optical densities. To try to clarify the dependence of the variations in physical parameters due to variations in physiological parameters, we modified the aforementioned matching simulation algorithm by introducing the fundamental response curve generating model (CIE, 2007). This model allows one to generate fundamental response curves by specifying the values of the macular pigment and photopigment optical densities, the yellowing of the lens with age, and the wavelength of maximum sensitivity of the L–M–S cone photopigments in a similar way to Smith et al. (1976). The resulting response curves are normalized to a maximum value of unity for each observer. To link these LMS fundamental response curves with RGB colour matching functions such as those obtained by Stiles and Burch (1955), one has to determine a 3 × 3 matrix whose elements are obtained with the following boundary conditions: since the Stiles and Burch matching functions were obtained using primaries of 444.44, 525, and 640 nm wavelengths, the function R must be zero for values of 444 and 525 and unity for 640; and analogously for the functions G and B, with the respective wavelength having the value unity.

Using this model, we studied the effect of variations in the physiological parameters on the optical wavelength of the two blue-yellow matches to the white-light continuum we are working with. The procedure was as follows:

(1) Generate the normalized fundamental response curves for some given values of the physiological variables.

(2) Obtain the elements of the matrix that transforms these fundamental response curves to RGB colour matching functions equivalent to those obtained by Stiles and Burch.

(3) Run the algorithm that gives the optimum energies of the yellow and blue spectral stimuli and the optimal wavelength of the blue stimulus for each of the two matches.

The results are presented in Table 3. One observes that variation in any of the physiological variables covered in this study leads to a variation in both the optimal wavelengths found and the distance between the two optimal wavelengths. Also, as was to be expected, the energy ratio values of both spectral stimuli vary in response to changes in the physiological parameters.

At first sight, these variations follow no clear pattern. A correlation analysis, however, showed that there is a clear correlation [Pearson Correlation Coefficient (PC) 0.928, with a Significance Level (SL) of 0.01] between the ratio K1 of the energies of the spectral stimuli in Match 1 and the optimal wavelength chosen by the observers. Also, there is a very strong correlation (PC 0.890 SL 0.01) between K2 and k2. These two correlations indicate that the choice of optimal wavelength determines the ratio of the energies needed to achieve a match. There is another very strong correlation (PC 0.916 SL 0.01) between k1 and k2, i.e. in all cases the distance between the two wavelengths

is related to the fixed distance between the yellow spectral stimuli. This is seen clearly in our experimental data where Dk is practically equal to 8 nm in all cases.

Table 3. Results of two blue-yellow matching simulations for different physiological parameters (the parameter changed is shown in bold italic type).

Observer	1	2	3	4	5	6	7	8	11	9	10
Age	32	***60***	32	32	32	32	32	32	32	32	32
O.D. macular pigment	0.35	0.35	***0.70***	***0.15***	0.35	0.35	0.35	0.35	0.35	0.35	0.35
O.D. L-cone pigment	0.5	0.5	0.5	0.5	***0.3***	***0.8***	0.5	0.5	0.5	0.5	0.5
O.D. M-cone pigment	0.5	0.5	0.5	0.5	0.5	0.5	***0.3***	***0.8***	0.5	0.5	0.5
O.D. S-cone pigment	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	***0.2***	0.4	0.4
k_{max} L-cone (nm)	558.9	558.9	558.9	558.9	558.9	558.9	558.9	558.9	558.9	***557.0***	***561.0***
k_{max} M-cone (nm)	530.3	530.3	530.3	530.3	530.3	530.3	530.3	530.3	530.3	530.3	530.3
K_1	1.30	1.26	1.60	1.15	1.36	1.21	1.51	1.05	1.34	1.33	1.27
k_1 (nm)	482.8	484.1	487.3	480.4	483.3	482.0	485.1	479.0	481.8	483.1	482.6
K_2	1.99	2.02	2.47	1.71	1.87	2.16	2.21	1.69	2.05	1.99	1.99
k_2 (nm)	489.9	491.8	494.6	487.0	489.5	490.3	491.0	488.0	488.8	489.9	489.9
Dk (nm)	7.1	7.7	7.3	6.6	6.2	8.3	5.9	9	7.0	6.8	7.3

Besides the aforementioned correlations, the statistical analysis of the simulation data showed other correlations whose explanation is less clear, but which indicate interesting new lines of inquiry. There is a correlation (PC)0.888 SL 0.01) between the quotient of the two matching ratios, K1/K2, and the L-cone photopigment optical density, and another correlation (PC 0.788 SL 0.01) between Dk and the M-cone photo-pigment optical density. Naturally, both correlations need to be confirmed experimentally in some future study.

Acknowledgements

The authors wish to thank the Spanish Ministry of Education and Science for its support through grant FIS2006-06110. This work has been partially funded by the European Regional Development Fund through the Regional Government of Extremadura (grant GRU09018).

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