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Measurements of the spectral modulation sensitivity function for two normal observers with CRT monitors

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Abstract. We have measured the sensitivity of the human visual system to chromatic stimuli of single chromatic frequency, ranging from 0.2 to 8.2 cycles/400 nm, and for eight initial phases from 0° to 315°. The optimal phase curves obtained for two observers show a CSF-type shape, with minima at certain frequencies which did not appear in previous computational predictions. The implications of a value of the cut-off frequency of somewhat less than 8 cycles/400 nm are also discussed.

Keywords: Chromatic frequency, spectral modulation sensitivity

Mesurés de la fonction de sensibilité à la modulation spectrale pour deux observateurs normaux avec écrans cathodiques

Résumé. Nous avons mesuré la sensibilité du système visuel humain aux stimuli chromatiques monofréquence, dans l'intervalle 0,2 à 8,2 cycles/400 nm, et pour huit phases initiales entre 0° et 315°. Les courbes de phase optimales obtenues pour deux observateurs montrent une courbe de forme CSF avec des minima à certaines fréquences qui n'apparaissaient pas dans les prévisions théoriques. On discute également des implications d'une valeur de la fréquence de coupure bien inférieure à 8 cycles/400 nm.

Mots clés: Fréquence chromatique, sensibilité à la modulation spectrale

1. Introduction

The spectral modulation sensitivity function (SMSF) is intended to characterize the human visual system in its properties as a filter of the information in chromatic frequencies. This term, chromatic frequency [1], is associated with the Fourier transform of spectral magnitudes, such as the spectral reflectance of an object or the spectral sensitivity of a visual mechanism. In this way, if a function is dependent on the wavelength, expressed in nm, its transform is a function of the chromatic frequency, expressed in cycles/nm.

In the field of vision, it is customary to work with spatial or temporal frequencies, the former visualized by sinusoidal spatial gratings and the latter by alternating lights; however, it is undoubtedly novel to inquire into the meaning of a spectral function which contains a single chromatic frequency. Perhaps the most illustrative case would be to consider the light from a source for which the spectral-power distribution (SPD) corresponded to a sinusoid of a particular frequency, as shown in figure 1.

We know that in nature no sources of radiation have an emission of the type shown in the figure. Neither are there artificial sources which emit in this way, regardless of the frequency. Only by optical devices in the laboratory can we obtain these SPDs.

Nevertheless, any colour signal has a content in chromatic-frequency information. In figure 2, we show the SPD of a measurement of daylight and a fluorescent tube (figure 2(*a*)), and the amplitude of their Fourier transform

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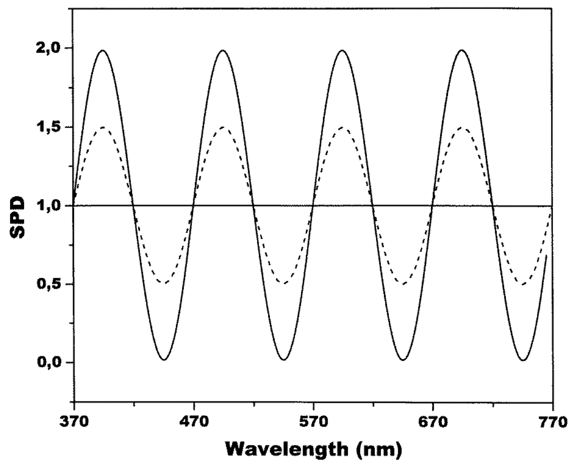

Figure 1. Sinusoidal SPD of frequency 4 cycles/400 nm, and relative amplitudes of 1, 0.5 and 0.

(figure 2(*b*)). With daylight, we see that the amplitude of the Fourier transform decays rapidly, with little contribution for frequencies of more than 0.02 cycles/nm, despite the pronounced minima at certain wavelengths, caused by the absorption of water vapour, ozone, CO_2 and other components of the terrestrial and solar atmosphere. The behaviour of the fluorescent tube is different, with some considerable contribution at high frequencies. Analogously, other sources, such as incandescent lamps and Xe lamps, present smooth profiles. However, Hg lamps and spectral lamps generally register maxima of narrow emission at certain wavelengths which can lead to a high content in higher chromatic frequencies.

As a result, we might inquire into the processing, in the human visual system, of these colour signals. Is all the information of the colour signal captured? If not, what part is left out? In other words, we might ask what we can deduce considering that, in colour vision, the visual system acts as a filter that relates an incoming signal, the colour signal, to the final response, the overall chromatic perception of the stimulus.

2. Antecedents

A preliminary approach to this study is the work of Barlow [2], in which he presented the Fourier-transform amplitude from the action spectra of cones deduced by Smith and Pokorny [3]. The results show that the transform amplitude decays almost to zero at certain frequencies, at which the photoreceptors appear to function as chromatic-information filters of the colour signals. From his results, it can be deduced that the demodulation is different for each cone, on having differing spectral bandwidths.

The action of radiation detectors in the chromatic-frequency domain, characterized by the Fourier transform of their spectral sensitivities, provides valuable information on the upper limit that can be reached by the cut-off frequency in the human visual system. Nevertheless, for our study, we need to consider the subsequent stages of the visual mechanisms that enable final chromatic perception.

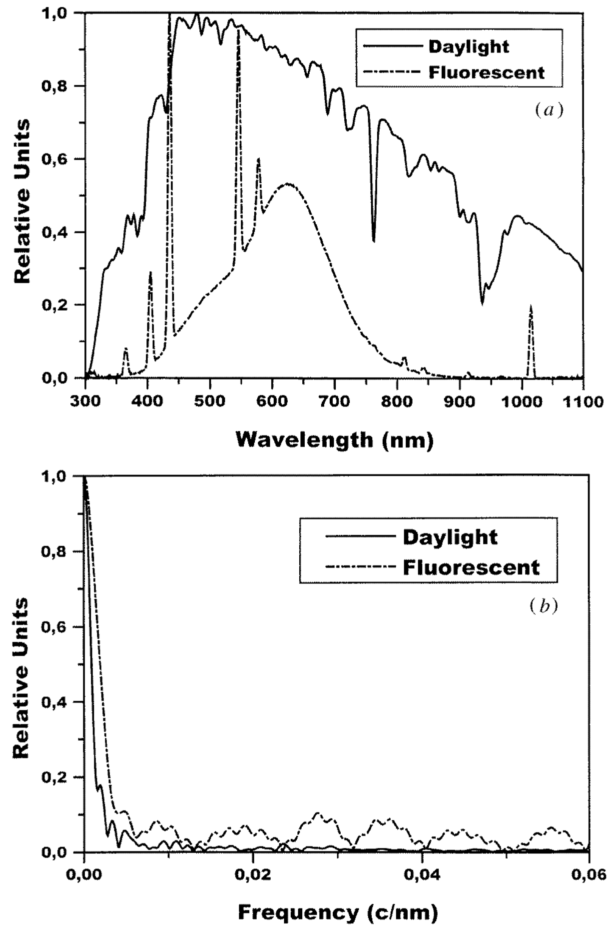

Figure 2. (*a*) SPD of daylight and fluorescent sources. (*b*) Fast Fourier transform of the former SPDs.

To date, two strategies have been designed. First, to calculate the response of the visual system to colour signals of a single chromatic frequency, such as that shown in figure 1, on the basis of colour-vision models [4]. Second, to measure a function of psychophysical transference, which we call SMSF, in real or simulated observers.

Benzschawel *et al* [4] compared different colour-vision models on the basis of the responses of the colour-vision mechanisms proposed in these models to colour signals described by the equation

$$E(\lambda) = E_0[1 + m\sin(fp(\lambda) + p_0)] \qquad (1)$$

where f is the chromatic frequency of the signal, m the relative amplitude (with values within the interval [0,1] and p_0 the initial phase. The function $p(\lambda)$ allows us to change a wavelength spectrum measured in nanometres to a phase characterization between 0° and 360°.

These authors were interested principally in determining the differences between models, with respect to the responses by normal and anomalous observers. Nevertheless, it is useful to emphasize that all of the models generate sensitivity variations with pronounced minima when the frequency varies (also when the initial phase changes). We have corroborated this result [5] in studying individual responses of colour-vision mechanisms involved in the chromatic-opponent models.

An initial experimental measurement of the SMSF was obtained by Barlow *et al* [6]. These researchers used an interferometric device that enabled them to characterize both the frequency and phase of the human SMSF, though these were not independent of each other. Afterwards, Bonnardel and Varela [7] avoided this latter aspect. They used periodic spectral-distribution stimuli produced by a combination of polarized filters that enabled, through square periodic modulations, the selection of spectral-power distributions of frequencies within 0.5 and 3.6 cycles/300 nm, and a phase from 0° to 180°. In a recent work Bonnardel *et al* [8] used liquid crystal displays to modify the spectral power distribution of a Xe lamp, and again measured the SMSF for 12 frequencies between 0.44 and 3.96 cycles/400 nm, varying the phase during each experimental session.

Our research has had a preliminary phase in that we obtained the SMSF by computer simulation [9]. In the second phase, we made experimental measurements, the results of which are presented in this work. Before we describe and discuss our results, it might be useful to provide a brief summary of what we call SMSF and the general method of measurement and calculation which we have followed in our laboratory.

3. The SMSF

To obtain a psychophysical function which could evaluate the transference of information in chromatic frequencies by the visual system, we have used the analogy with the now well known functions CSF and TMTF, which serve comparable purposes in the domain of spatial and temporal frequencies. Thus, we evaluated the response to SPDs of a single chromatic frequency, by comparing these with a flat SPD stimulus, absent, therefore, from spectral modulation. This evaluation was made with the determination of the minimum spectral contrast, the difference between maxima and minima of the SPD, which allowed a perceptual difference between the stimulus of the single chromatic frequency and the flat SPD.

In analytic terms, this means conducting experiments that, in principle, compare a SPD stimulus represented by expression (1) with $m = 1$ (figure 1) with an equal-energy stimulus, and progressively decreasing m in the first stimulus until reaching a stimulus indistinguishable from the second. Since we have taken the visible spectrum between 370 and 770 nm, and the frequency f in cycles/400 nm, the expression for $p(\lambda)$ is given by:

$$p(\lambda) = (0.9\lambda - 333)^{\circ}. \qquad (2)$$

This procedure is analogous to that used in the CSF, with the decrease of the spatial contrast in sinusoidal gratings until the fringes are no longer perceived.

Then the contrast threshold is determined as:

$$C = \frac{E_{\max} - E_{\min}}{E_{\max} + E_{\min}} \qquad (3)$$

$E_{\max}$ and $E_{\min}$ being the maximum and minimum values of the SPD of a single chromatic frequency when the value m is reached, which generates a stimulus indistinguishable from the equal-energy one. It is immediate then to calculate:

$$C = m \qquad (4)$$

and, consequently, we can define the sensitivity, S, as:

$$S = \frac{1}{m} \qquad (5)$$

in strict analogy with that used in the calculation of the visibility in the determination of CSF.

This term 'visibility' is identified more with concepts which are more spatial than spectral. Therefore, although we used the term when we published our computational determination of the SMSF [9], in the future we shall use the term 'sensitivity', in agreement with other authors [7, 8].

Given an initial phase and repeating this process for chromatic-frequency stimuli in a broad interval, we can obtain the SMSF function, which characterizes the visual system in this domain.

Bonnardel and Varela [7] followed a similar procedure, except without making a simultaneous comparison between stimuli, but rather, beginning with an unmodulated stimulus, increased the modulation until the observer appreciated a chromatic sensation different from the initial achromatic one. The path is the reverse of that described earlier and the comparison is, in a certain sense, successive in nature. In their last study Bonnardel *et al* [8] used a three alternatives temporal forced-choice method, introducing random luminance variations between successive stimuli in order to try to avoid the effects of the variations in brightness of their stimuli. In any case, all these procedures are applicable to the determination of the SMSF, although they can bring about some quantitative differences in the results.

4. Experimental measurements

We chose to perform the experiments with a CRT monitor, with which we were able to obtain metameric stimuli at those of the SPD of a single chromatic frequency. These types of measurements with a CRT monitor present advantages and disadvantages with regard to the use of optical devices. The principal disadvantage is that, for a strictly correct simulation, we must know the colour-matching functions of each observer participating in the experiment. In this way, we generate metameric stimuli of the SPD of a single chromatic frequency for each observer. Not having the colour-matching functions for each observer, we used those of the CIE 1931 Standard Observer. We estimated that, by using the colour-matching functions of the CIE 1931 Standard Observer instead of those of each observer, we introduce less error into the generation of the stimuli than that found experimentally using optical methods to attain the SPD of strictly sinusoidal profiles.

The advantages of using a CRT monitor to make the measurements include the ease of controlling the spatial

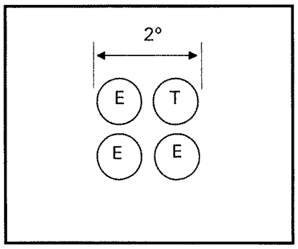

Figure 3. The observation field presented in the experiments. E represents the achromatic stimulus, T the stimulus corresponding to a given chromatic frequency and relative amplitude.

and temporal presentation of the stimuli (spatial distribution of these, field size and sequencing) and in controlling adaptation.

We used a Samsung monitor (model CSD5577) controlled by a computer with an Intel 80486 processor at 33 M with a Tigastar 24-bit video card. This monitor was calibrated assuming the hypothesis of spatial independence, phosphorus independence and spatial independence with a simple-scale factor [10, 11]. We also verified previously the linearity and additivity in the monitor. In accord with previous works in our laboratory [12], phosphorus constancy was not assumed and thus, for each monitor gun, we measured the spectral radiance for the entire range of entry values (0–255), taking every third value. These measurements were made with a Spectrascan PR-704 spectroradiometer from Photo Research.

The calibration data served as entry data for a calculation program which relates the DAC entry values of the monitor guns with the chromaticity coordinates generated. In this way, if we wish to obtain a certain stimulus on the monitor which corresponds to a single SPD frequency, we first calculate its chromaticity coordinates and then the DAC values which must be supplied to the monitor.

The calibrations were repeated periodically following the protocol established in previous works [12]. The monitor was turned on 30 min before beginning an experimental measurement session.

The observation field (figure 3) is composed of four stimuli observed simultaneously, of which three correspond to the equal-energy stimulus, and the rest to the test stimulus. The field size is $2 \times 2°$. The observer is situated 1 m away and the type of vision is central, monocular and direct, with natural pupil.

The type of field was the same as that used by Krauskopf and Gegenfurtner [13] and the experimental method was also similar. As in the case of these authors, the task of our observer at each stimulus presentation was to indicate the position (among four possibilities) of an unequal-energy stimulus by pressing a computer key. In the event that no differences between the stimuli were perceived, the observer was to indicate a position at random.

The test was presented for 1 s, a habitual exposure time in these types of experiments [14]. The background for the test consisted of an achromatic stimulus ($x = 0.306$, $y = 0.329$) of low luminance (1.71 cd m^{-2}) which was maintained over each entire experimental session. The sessions began with a 2 min period of darkness adaptation followed by 5 min of adaptation to the achromatic background. The experimental sessions (including the adaptation periods) lasted 30 min.

Two observers participated in the experiments: JA (aged 38 years) and EV (aged 23 years). They were classified as normal observers, according to the Ishihara test confirmed by the Heidelberg anomaloscope (Nagel type).

We obtained the SMSF for eight initial phases: 0°, 45°, 90°, 135°, 180°, 225°, 270° and 315°. The chromatic frequencies at which we determined their sensitivity at each SMSF were from 0.2 to 8.2 cycles/400 nm, at intervals of 0.2 cycles/400 nm. In some cases, the upper limit was less (to 7.0 cycles/400 nm), since the carrying out of the experiments could obviate the need to study higher frequencies.

The luminance level of the stimuli was maintained constant in all the experiments at 20 cd m^{-2}. Our intent was to work at a photopic level, in the zone in which the monitor additivity was secure and with the convenience of not working near the maximum limits of activation of the monitor guns.

In each experimental session, we took measurements in relation to obtaining the SMSF of a particular initial phase and for four chromatic frequencies. Given an initial phase and a chromatic frequency, the stimuli with different modulation levels (m from 1 to 0) were situated, in the chromatic diagram, at the line which joins the $m = 1$ stimulus (maximum modulation) with the equal-energy one. In each of the four possible lines selected for an experimental session, five stimuli were studied, which were presented a total of five times, distributed randomly over the session. Thus, the test was presented a total of 100 times in each session.

Each stimulus to be compared with the equal-energy one was presented 15 times, though in the cases in which the observer discerned clear differences in the test stimuli, the number of presentations was less. In this case, we reduced the number of measurements and made a stronger effort in the zone of uncertainty, where we tried to determine the point of the diagram which we could consider the threshold limit. For this, the stimulus for which 70% of the responses were correct in the test was determined either directly or by linear interpolation in the distribution of correct responses over the entire line. In this way, we determined the value of m, which enabled us to calculate the sensitivity, S, for each frequency and initial phase. We chose 70% correct responses as the criterion, rather than 50%, because to this percentage we added an estimation of correct random responses. In this way, we knew that on the threshold, the observer had responded correctly to the different stimuli at least 45% of the time.

As can be deduced, for each S value, it is necessary to take measurements in different experimental sessions. This enables us to average a certain temporal variability under the psychological conditions of the observer.

Table 1. Cut-off frequencies for both observers and all phases.

Phase (degrees)	EV (cycles/400 nm)	JA (cycles/400 nm)
0	5.6	5.6
45	7.4	7.6
90	6.6	6.8
135	7.0	7.0
180	5.6	5.6
225	7.8	7.6
270	7.4	7.2
315	7.0	7.0
Average	6.8	6.8

5. Results

Figures 4(*a*)–(*d*) show the SMSF obtained for some initial phases by the two observers. Two general features are immediately evident: (1) the overall agreement of the results between the two observers, though certain discrepancies arise for 90° and 270°; (2) the broken profile which might be expected from the computational predictions [9].

The increase in sensitivity with frequency for low frequencies, its decay at high frequencies and some of the minima found at intermediate values can be explained by the fact that the extreme points of the chromatic-frequency interval studied present chromaticity coordinates so close to the equal-energy one that the stimulus with $m = 1$ is now indistinguishable from the previous one (it falls inside the threshold) or a small decrease in $m = 1$ causes this to happen. As a result, for these frequencies, we find sensitivity values of 1 or slightly higher.

The presence of the minima at intermediate frequencies is more difficult to explain. We can estimate that, in some cases, the minima are presented for frequencies of which the stimuli fall on or near the tritan confusion line; nevertheless, we cannot generalize this statement. The same occurs with the frequencies situated on the red–green confusion lines, in some cases appearing to be minima, and in others maxima. We are aware that, although the discrimination in general becomes poorer for the tritan confusion line, interaction effects can arise among opponent mechanisms, in relation to the discrimination [15], which causes the frequencies of poorer discrimination not to coincide with those situated on this line.

With regard to the cut-off frequencies found, hardly any differences appear between complementary phases, except in the case of 90° and 270° (table 1). As we see, the cut-off frequencies go from 5.6 to 7.8 cycles/400 nm, depending on the initial phase. The average is, for both observers, 6.8 cycles/400 nm (0.017 cycles/nm). This value is greater than that set by Bonnardel and Varela [7] and only 1.1 cycles/400 nm greater than that set by Bonnardel *et al* [8], calculated by extrapolation. The cut-off frequency of the optimal phase curve would be the highest (7.8 cycles/400 nm) and therefore very close to that obtained in the computational simulation for three MacAdam units (8 cycles/400 nm).

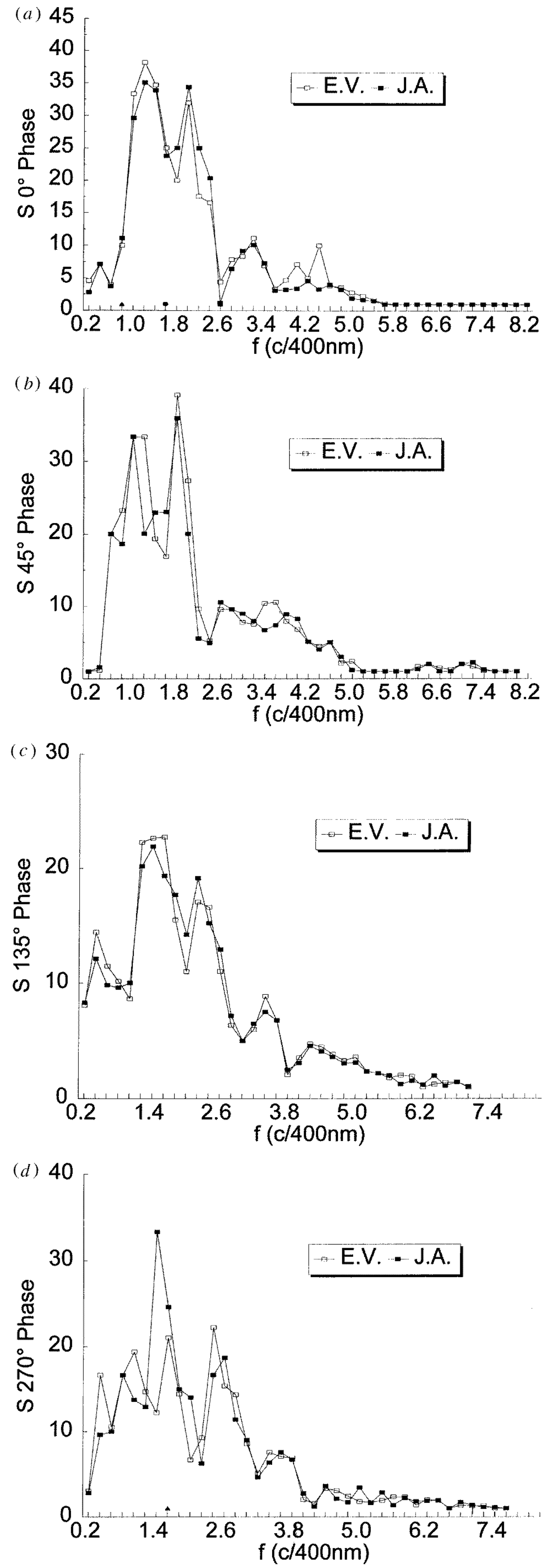

Figure 4. The experimental results for both observers and phases at (*a*) 0°, (*b*) 45°, (*c*) 135°, (*d*) 270°.

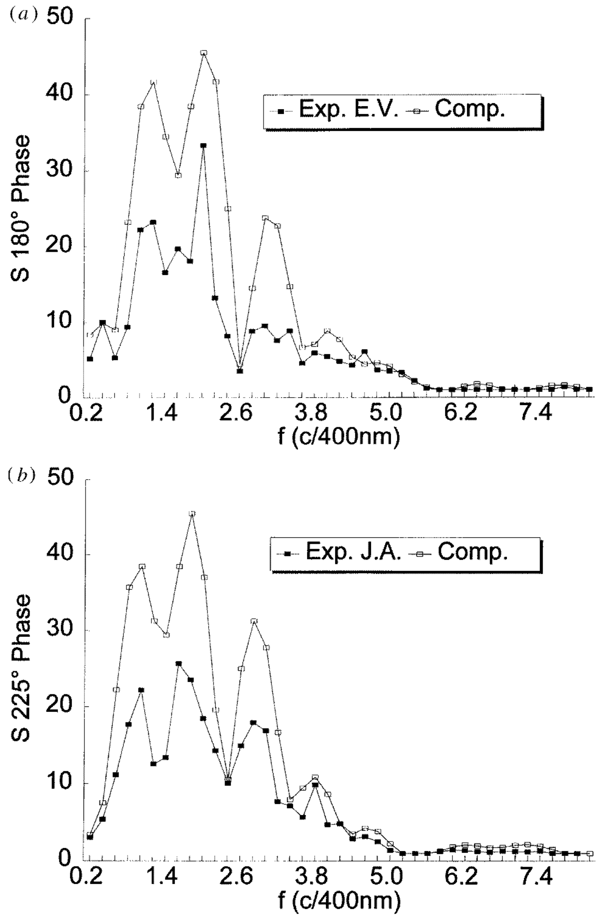

Figure 5. Comparison between experimental and computational results for phases at (*a*) 180°, (*b*) 225°.

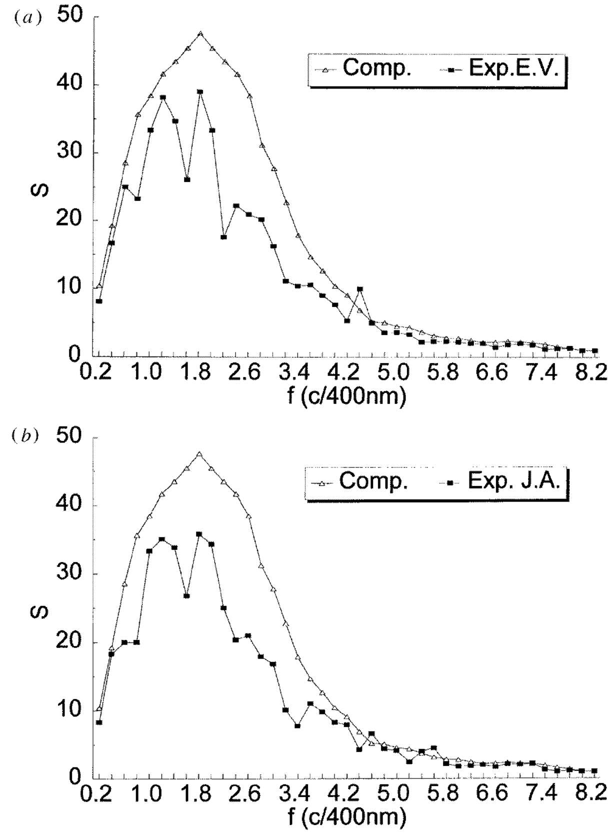

Figure 6. Comparison between experimental and computational optimal curves for (*a*) observer EV, (*b*) observer JA.

Figures 5(*a*) and (*b*) present a comparison of computational and experimental SMSFs, having chosen from among the former those corresponding to three MacAdam units, by the similarity in the cut-off frequency of the curves. Overall, the location of the peaks which appear is highly similar in the two types of results. At most, we find a shift of 0.4 cycles/400 nm in frequency.

Despite these similarities, we cannot state that the experimental SMSFs are a copy of the computational ones, simply with a shift towards lesser S values, since the differences between the experimental and computational values are far from being constant for frequency and phase. As can be seen, in the experimental SMSFs, the differences between maxima and minima found in the computational SMSFs are softened. This happens despite the analogous behaviour of the results for high frequencies and the similarity among cut-off frequencies.

The differences found between experimental and computational results may be caused by the fact that the latter were obtained using MacAdam discrimination data [16], based on the experimental differential chromaticity threshold measures by MacAdam [17], for one observer and using a matching method. So, not only do both sets of results differ in the observers employed, but also in the experimental methods used.

To delve into the analysis of these results, we obtained the optimal and pessimal phase curves of the experimental results. In figures 6(*a*) and (*b*), we compare the optimal phase curves obtained by the two methods for both observers. This confirms the similarity of the results at high and low frequencies. Nevertheless, at intermediate frequencies, not only are lower values obtained in the experimental frequencies, but we are also struck by the appearance of the minima in the curve, which were not obtained with the computational calculation. In this latter case, we can state that obtaining the curve averaged the results, in a sense, for the different phases, leading towards the disappearance of the typical minima of the curves for each phase.

The results for the two observers were very similar, with differences, at most, of 0.2 cycles/400 nm in the frequency in which the minima appeared, although the two coincided where the minimum was most pronounced, 1.6 cycles/400 nm. Figure 7, in which we present the average optimal and pessimal phase curves for both observers, shows this minimum clearly, together with a less-pronounced one at 0.8 cycles/400 nm in the optimal-phase curve. In the pessimal, we find a maximum for 1.6 cycles/400 nm, which testifies to the singularity of this frequency. In principle, therefore, there appears to be a loss of sensitivity of the human colour-vision system at SPDs of this frequency.

To compare our results with those of Bonnardel and Varela [7] and Bonnardel *et al* [8], we have represented

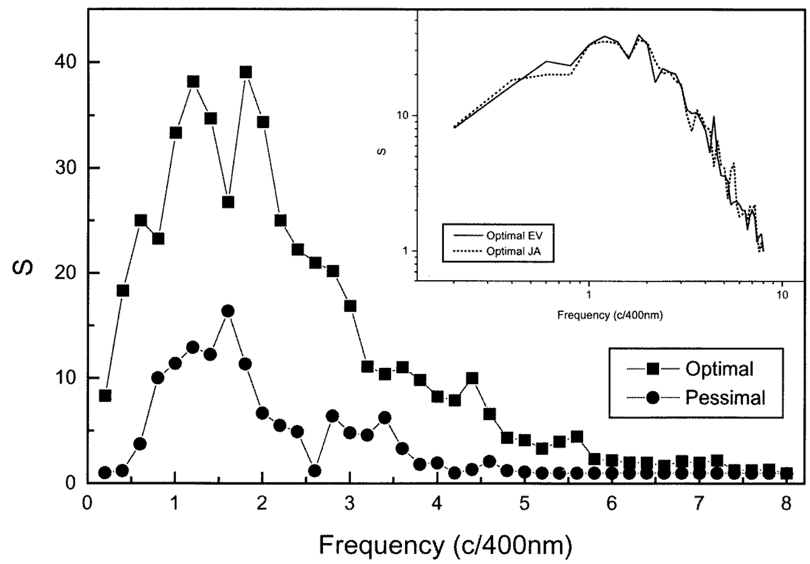

Figure 7. Optimal and pessimal curves for both observers. Inset: optimal curves for observers EV and JA on a logarithmic scale.

in figure 7 (inset) the optimal phase curve in logarithmic scale also. The results of these authors, shown according to observers, also present a certain presence of minima and a clear loss of sensitivity for high frequencies. Nevertheless, conclusions cannot be drawn concerning the lowest sensitivity values at certain intermediate frequencies. Thus, the decay of the SMSF towards low frequencies is not of the same type as that found in our experiments, since ours has a more pronounced slope. The cause of this may be the square modulation used by Bonnardel and Varela [7] or the fact of working at constant luminance in our experiments, while Bonnardel *et al* have some luminance variations and work at a mean luminance of 5–6 cd m^{-2}, much lower than ours. This fact, and the different chromaticity coordinates of the unmodulated stimulus in our work, could explain the variations found in the global values of sensitivity of the curves.

6. Discussion

In view of the results obtained in measuring the SMSF, we can state that the human visual system, with respect to information at chromatic frequencies, acts like a band-pass filter. The form of the SMSF, taken as the optimal phase curve of the measurements for the different initial phases, recalls that of the CSF or the TMTF, with a growth of S as the chromatic frequency rises, until reaching the maximum values between 1 and 2 cycles/400 nm, and a subsequent rapid decay to the cut-off frequency. With our experimental method, we can evaluate this at a value of somewhat less than 8 cycles/400 nm, or 0.02 cycles/400 nm, which is equivalent.

Nevertheless, we have found discontinuities in the smooth shape of the curve for certain chromatic frequencies. Although we believe that some of these appear with sufficient clarity, especially when we use a linear scale in the representation, we recognize that we must broaden our study to a greater number of initial phases, which would confirm these minima or eliminate them.

In any case, it is notable that, though the sensitivity is determined for eight initial phases, at the frequency of 1.6 cycles/400 nm, we do not reach a sufficiently high S value, comparable to those of the adjacent frequencies. Furthermore, when we examine the shape of the curve, we find that it is precisely at this frequency that the SMSF maximum would be expected.

In addition, the fact that at this frequency the maximum of the pessimal phase curve appears indicates the narrow range of variation in the sensitivity at this frequency, in comparison with the rest of the frequencies close to this one which were studied.

The predictions according to the vision models also lead us to expect the presence of sensitivity maxima and minima in the curves of each initial phase [4]. Pronounced minima appear in the results of these authors, although this does not happen for the same chromatic frequencies as in our case. Thus, these authors, for the phase of 0° and most of the models analysed, show minima of around 0.9 cycles/300 nm (1.2 cycles/400 nm), 2 cycles/300 nm (2.7 cycles/400 nm) and 3 cycles/300 nm (4 cycles/400 nm), whereas in our case the minima are 0.6, 1.8, 2.6 and 3.6 cycles/400 nm (figure 4(*a*)).

As we can see, although some frequencies coincide—as does the type of variation in sensitivity with the frequency, to a certain extent—our results differ from the predictions of the models, especially at low frequencies in which the sensitivity values are clearly lower.

We have investigated the implications of the fact that the human visual system has a cut-off frequency equal to or less than 0.02 cycles/nm. To illustrate the possible responses, we have chosen an example. We have taken a colour signal with a large content of high frequencies. Figures 8(*a*) and (*b*) show the signal chosen as well as its transform. As can be seen, we have simulated in the signal a SPD with 10 narrow maxima, in such a way

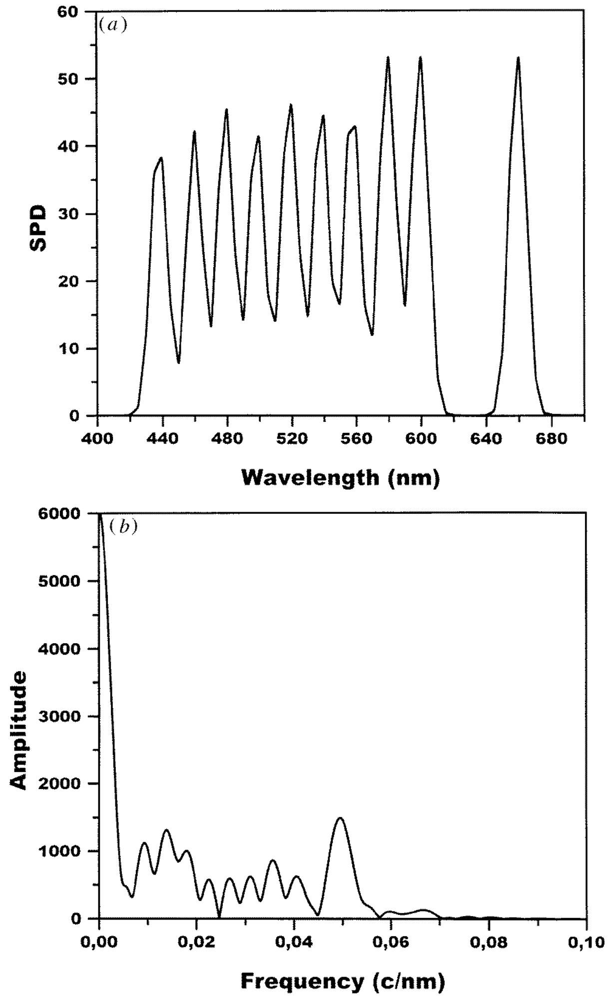

Figure 8. (*a*) SPD of a signal with high content of chromatic frequencies above the cut-off of the SMSF. (*b*) FFT of the former signal.

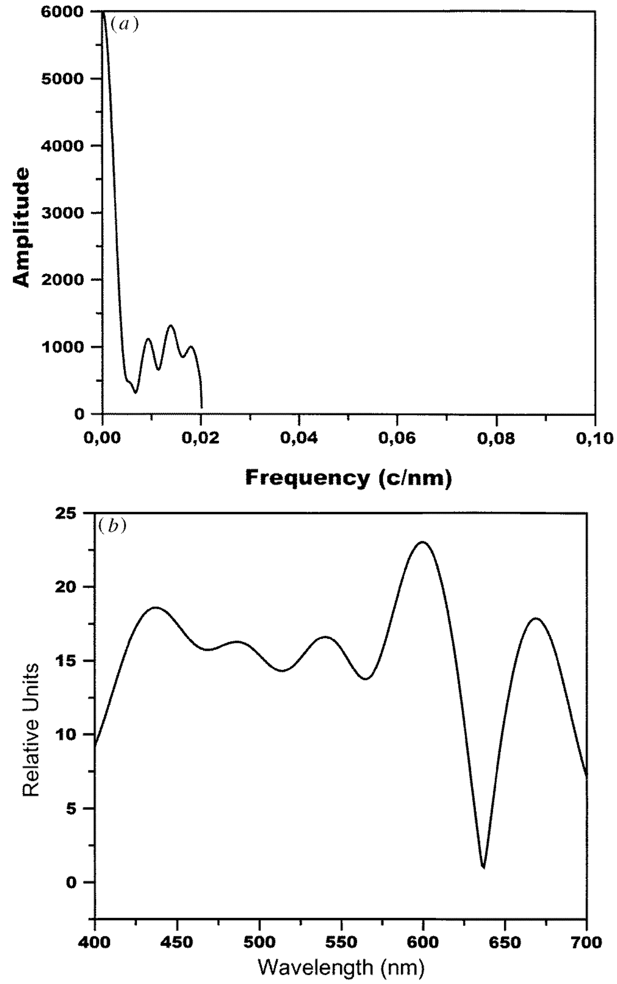

Figure 9. (*a*) FFT of the signal of figure 8(*a*) in which the contents above 0.02 cycles/nm have been suppressed. (*b*) Inverse FFT of the signal of figure 9(*a*).

that its transform presents a large content for frequencies higher than 0.02 cycles/nm. Afterwards, we attained a signal for which the Fourier transform had the same values in low frequencies as the previous and which is cancelled for values over 0.02 cycles/nm. This signal and its transform is shown in figures 9(*a*) and (*b*). The differences in the spectral profiles of the two colour signals are notable, although their chromaticity coordinates are the same: $x = 0.315$, $y = 0.392$.

This example indicates a possible method of obtaining metameric lights, by reverse Fourier transform of the truncated transform from 0.02 cycles/nm. Analogous results can be obtained by truncating the transform to different frequencies higher than 0.02 cycles/nm.

In the example of figures 8(*a*), (*b*), we have shown a colour signal for which the content in chromatic frequencies is high at frequencies above the cut-off of the SMSF. We wish to emphasize that although in many colour signals in everyday life, as shown in figure 2, the information is contained in the interval in which the SMSF is defined, there are many other signals, such as those corresponding to quasimonochromatic spectral lights, etc, which present a content of information at high frequencies exceeding even that shown in figure 8. This information is filtered by the visual system, thus being lost in the final chromatic perception.

It should be understood that the filtering of the visual system not only affects the frequencies above the cut-off, but also that at intermediate or low frequencies, as we have seen, the sensitivity varies, and thus the perception is affected by the different treatments of each frequency. Furthermore, both in our results, and in those of Bonnardel and Varela [7] and Bonnardel *et al* [8], maxima and minima appear in the SMSF, indicating a discontinuous treatment of the information.

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