# Models of the visual system and their application to image-quality assessment

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## ABSTRACT

The spatiochromatic properties of the human visual system are described in terms of the contrast-sensitivity function (CSF). An experiment is described that measures the luminance CSF for achromatic and chromatic stimuli. The contrast detection thresholds are found to be higher for chromatic stimuli indicating that the sensitivity of the luminance channel to contrast is less for these stimuli than for achromatic stimuli. A computational model is presented that is able to predict the psychophysical data. The implications for models of image-quality assessment are discussed. Traditional estimates of the luminance CSF based upon achromatic stimuli may over-estimate the visual system's sensitivity to luminance contrast in colour images.

## 1. INTRODUCTION

The colour properties of the human visual have been extensively studied and the CIE 1931 XYZ system is an empirical model (based indirectly on the human cone response functions) that allows the matching condition for spatially uniform stimuli to be defined. However, the original CIE system was concerned with colour matching rather than colour appearance. Extensions of the original CIE system, most notably CIELAB and more recently advanced colour-appearance models, attempt to address the issue of colour appearance[1]. Some of these models can, for example, account for the change in colour appearance that occurs when an object is viewed against backgrounds of different colour. However, image quality is concerned with stimuli that contain both colour and spatial information and until recently models that could process such spatiochromatic stimuli were not widespread. The contrast-sensitivity function (CSF) can be thought of as the spatiochromatic equivalent of the colour-matching functions and is typically measured for the luminance, red-green and yellow-blue channels of the visual system. The CSFs are typically measured by recording the contrast at detection threshold (this being inversely related to sensitivity) for sinusoidal stimuli that are either achromatic (for the luminance channel) or iso-luminant (for the chromatic channels)[2]. The development of S-CIELAB demonstrates how models of CSFs can be combined with existing colour models to develop image-quality or image-difference metrics[3]. In S-CIELAB image-differences are computed on a pixel-by-pixel basis and the CIELAB colour-difference metric is used. However, prior to the calculation of these differences the images are convolved with spatial-filter versions of the CSFs which act as blurring kernels. So, for example, contrast at spatial frequencies higher than the cut-off frequencies would be totally attenuated since, it would be argued, the visual system has no sensitivity to contrast at these frequencies. However, the CSF of the visual system is more complex than the three

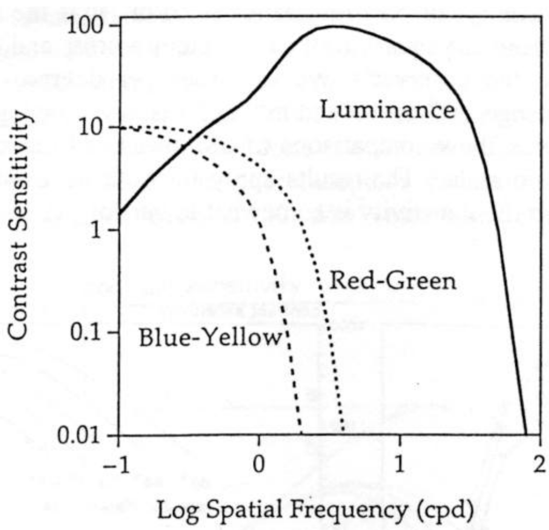


**Figure 1:** Schematic diagram of the CSF for the human visual system.

functions that are often presented (Figure 1). This paper describes the CSF in more detail, reports some new measurements of CSF, and introduces a new model of CSF that is specifically designed for use in image-difference and image-quality models.

## 2. SPATIOCHROMATIC PROPERTIES OF THE HUMAN VISUAL SYSTEM

Measurements of the luminance CSF show that under typical conditions the sensitivity is maximum for stimuli of approximately 6 cyc/deg and falls off for lower and higher spatial frequencies (the CSF is said to have a band-pass shape). The fall-off in sensitivity at higher spatial frequencies is not surprising since optical blurring by the lens reduces the contrast of high spatial-frequency stimuliu and retinal ganglion cells are less sensitive to such stimuli[2]. However, the eye's optics cannot account for the slight fall-off in sensitivity at low spatial frequencies (Figure 1); neural factors, such the properties of centre-surround receptive fields, must be responsible. The CSFs for the chromatic opponent channels are said to be low-pass in shape in that sensitivity decreases with increasing spatial frequency (Figure 1).

There is a great deal of evidence to support the notion that the visual system is adaptive[4]. In the case of CSF this means that the magnitude and shape of the CSFs change with certain properties of the stimulus. So, for example, the luminance CSF generally decreases with mean luminance and this is accompanied by a shift in peak sensitivity to lower spatial frequencies (indeed, for stimuli of very low mean luminance the luminance CSF becomes low pass). Note that if Weber's law was valid the luminance CSF would remain contrast for stimuli with different mean luminance. The reduction in luminance contrast sensitivity that is observed when the luminance f the stimulus is reduced therefore represents a break-down in Weber's law. It is also known that the CSFs vary with the temporal properties of stimuli. The spatiotemporal CSF has been measured for the luminance channel, for example, and sensitivity falls of for very high temporal frequencies. The work described in this paper is concerned with experiments to study whether the luminance CSF depends upon the colour of the stimulus. The significance of the results for image-quality assessment are discussed and a new computational model for luminance contrast sensitivity is proposed

## 3. EXPERIMENTAL

Psychophysical experiments were carried out with a VSG system and PSYCHO software (version 2.00). Achromatic stimuli were presented to observers who viewed the VDU screen from a distance of approximately 1m in a darkened room. Observers were instructed to fixate to a central point and to alter the luminance contrast for full-field sinusoidal stimuli at each of six spatial frequencies (2.53 5.29 9.7 14.54 19.39 29.09 cyc/deg). The luminance of the background field was fixed at 30 cd/m$^2$ but the chromaticity of this field was varied from neutral to being chromatic in each of eight colour directions (red, yellow, green, blue, cyan, lime, purple, orange). Part of these experiments have also been reported elsewhere[5,6]. Two male observers (aged 24 and 31) participated in the experiments.

## 4. RESULTS

Figure 2 shows the luminance CSFs that were measured (pooled over both observers). It is evident that the sensitivity to luminance contrast is consistently less for chromatic stimuli than for achromatic stimuli.

A computational model of the luminance CSF was developed that can account for the interaction between the luminance and chromatic channels. The model contains no dependence on eccentricity because it is intended for use with models of image-quality or image-difference metrics. The model is defined thus:

$$\mathrm{CSF}(u) = F_L F_C\, 0.28\, u \exp(-0.3u)\, [1 + \exp(0.3u)]^{0.5}$$

where $F_L = 1000(L/70)^{1/3}$ if $1 \leq L \leq 70$

$$F_L = 1000(1/70)^{1/3} \qquad \text{if } L < 1$$
$$F_L = 1000 \qquad \text{if } L > 70$$

and where $u$ is the spatial frequency in cyc/deg and $L$ is the mean luminance of the stimulus in units of cd/m$^2$.

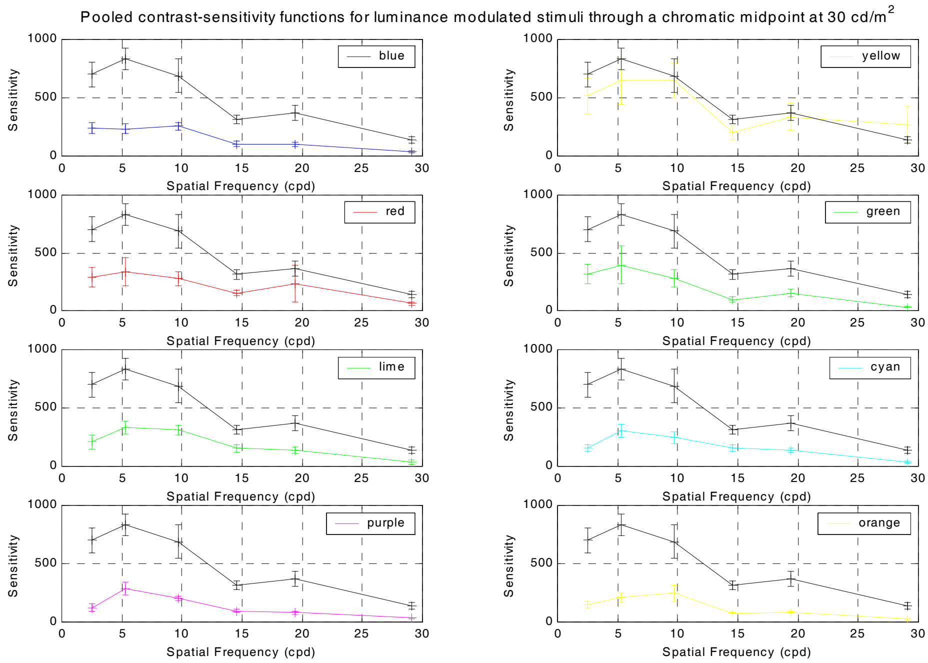


**Figure 2:** Pooled results for measurements of the luminance CSF for different colour stimuli. In each pane, the CSF for an achromatic stimulus is compared with the CSF for a chromatic stimulus. In every case the CSF for the chromatic stimulus is smaller than for the achromatic stimulus.

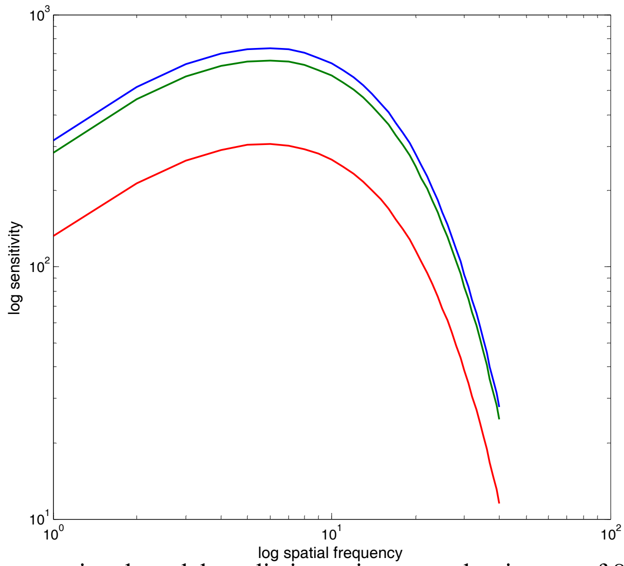


**Figure 3:** Computational model prediction using mean luminance of 80 (blue line), 50 (green line) and 5 (red line) cd/m$^2$ for achromatic stimuli.

Figure 3 shows the predicted luminance CSF of the model for three achromatic stimuli of different mean luminance. The sensitivity reduces with decreasing mean luminance in accordance with other studies and models and sensitivity declines for high and low spatial frequencies. The novel feature of the model is illustrated in Figure 4 which shows the luminance CSF predicted by the model for stimuli with mean luminance of 50 cd/m$^2$ and with various saturation. The saturation is computed by calculating the CIE XYZ values at each pixel in the stimulus image and then computing the average distance from the white point in the xy chromaticity diagram.

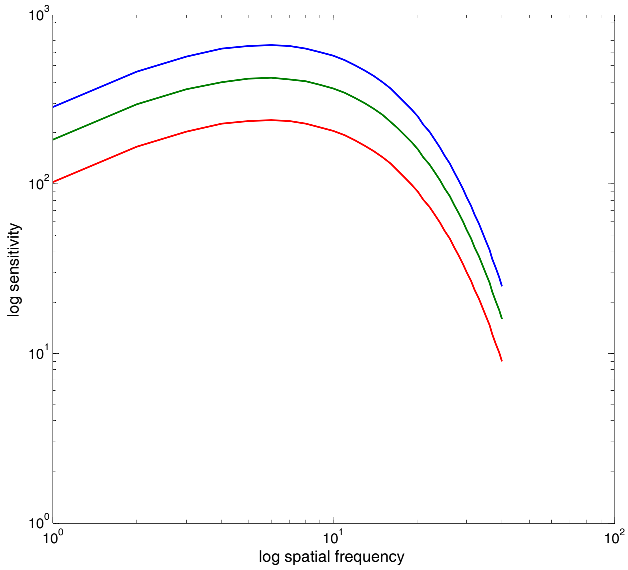


**Figure 4:** Computational model prediction using mean luminance of 50 cd/m$^2$ and mean saturations of 0 (blue line), 0.2 (green line) and 0.4 (red line).

## 5. CONCLUSIONS

Measurements of luminance contrast sensitivity have been made that show that the sensitivity of the luminance channel is less for chromatic stimuli than for achromatic stimuli. This finding suggests that luminance and colour information may not be processed independently and this in supported by some other related studies[7,8]. A computational model of luminance CSF has been developed and could be used by image-difference and image-quality models. This model takes account of the dependence of the luminance CSF on mean luminance and colour but does not include any dependence on eccentricity because the application of CSF in imaging technologies invariably is a global image-processing operation.

## References

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