Simulating images perceived by subjects with abnormal colour or spatial vision

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Abstract

We add a simple model for spatial vision to our original corresponding pair algorithm to simulate the colour appearance of an image, as seen by a subject with variant (abnormal) vision. In this way, the perception of coloured images by subjects having their spatial vision altered by a pathology, may be simulated, both for normal and dichromatic colour vision.

Introduction

Acquired vision defects, in particular those affecting ganglion cells in the Parvocellular or in the Koniocellular pathway provoke changes in the relative spectral sensitivities of the chromatic and achromatic mechanisms (see King-Smith, 1991 [1] for a review) and selectively reduce also chromatic and achromatic contrast sensitivity for certain spatio-temporal frequencies [2-5], altering therefore image perception. In this work, we propose a modification of the *corresponding pair algorithm* [6,7] to simulate how subjects with acquired vision defects see a colour scene. Although the examples shown below are based in a simplification of what really happens, the procedure can be used to gain some insight about how subjects with acquired colour vision defects see natural scenes.

Methods

The *corresponding pair algorithm* has been proposed as a method for simulating images perceived by dichromatic subjects of any type [6,7] using any colour vision model with normal and dichromatic versions, provided the model can be inverted [6,7]. We have reformulated the algorithm to simulate how any subject with variant vision perceives a scene. The appearance a stimulus $\mathbf{T}(x,y)$ has for a variant observer can be described if a stimulus $\mathbf{S}(x,y)$ is found that verifies that a normal observer experiences the same sensation viewing $\mathbf{S}(x,y)$ as the subject viewing $\mathbf{T}(x,y)$. If normal and variant versions of the same vision model are available, the tristimulus values of $\mathbf{S}(x,y)$ are obtained by applying the inverse of the normal model to the perceptual descriptors of $\mathbf{T}(x,y)$ computed with the variant model, i.e.:

$$\mathbf{S}(x,y) = m^{-1}\left(m(\mathbf{T}(x,y),\mathbf{p}_n),\mathbf{p}_v\right) \quad (1)$$

where m is a mathematical operator comprising all the transformations of the vision model, $\mathbf{T}(x,y)$ and $\mathbf{S}(x,y)$ are the triestimulus values of the original and simulated stimulus, for each spatial position (x,y), and $\mathbf{p}_n$ and $\mathbf{p}_v$ are, respectively, the set of parameters defining normal and variant vision. The form of equation (1) may be simplified if the algorithms of the normal and the variant models coincide beyond a given stage, since it would suffice to compute the inverse of the output of the last stage where the models differ.

The vision model must satisfy, at least, the following conditions: 1) the normal version of the model must be invertible, either analytically or numerically; 2) normal and variant versions must provide the same number of descriptors, to avoid an infinite number of solutions in Equation (1)) , and 3) the values of the descriptors computed for the variant subject, for each stimulus, must lie within the range of those for the normal subject, to avoid having "unreal colours" as solutions.

In this work we have used a simplified form of Equation 1, by assuming that the alterations suffered by a subject can be separated in changes affecting spectral sensitivity of certain colour mechanisms and changes in contrast sensitivity of certain spatial mechanisms (which are also colour selective). That is,

$$\mathbf{S}(x,y) = m^{-1}\left(m(\mathbf{T}(x,y),\mathbf{p}_{nc},\mathbf{p}_{ns}),\mathbf{p}_{vc},\mathbf{p}_{vs}\right) \quad (2)$$

where $\mathbf{p}_{nc}$ and $\mathbf{p}_{vc}$ are the set of parameters defining the spectral sensitivities of the colour mechanisms in the normal and variant versions of the model and $\mathbf{p}_{ns}$ and $\mathbf{p}_{vs}$ the parameters defining their spatial properties. Basically (see Figure 1), a colour vision model provides the responses of an achromatic ($\mathbf{A}(x,y)$), a red-green ($\mathbf{T}(x,y)$) and a blue-yellow ($\mathbf{D}(x,y)$) mechanism for each point of the image and spatial processing is then performed separately in these three mechanisms.

The colour model we have used here is Guth's ATD95[8]. Briefly, ATD95 is a three-stages model, including a gain-controlled non-linear cone-stage, an intermediate non linear opponent-stage leading to the responses of the achromatic (A_1), red-green (T_1) and blue-yellow (D_1) mechanisms, and a second linear opponent-stage leading to the responses of the final achromatic (A_1) and the final chromatic (T_1 and D_1)

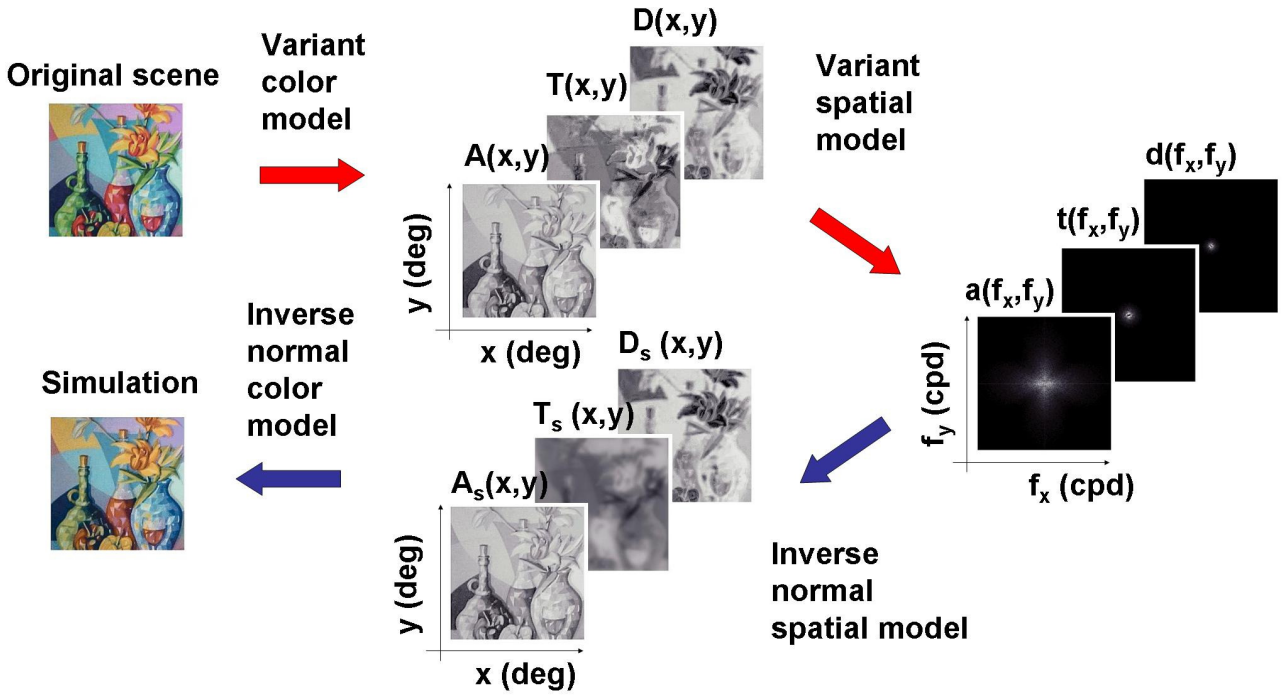

Figure 1. *Schema of the model used. The tristimulus values of the original scene enter the variant version of a colour vision model (ATD95), to yield three images, one for the responses each variant colour mechanism (achromatic A, red-green T and blue-yellow D). Separate linear variant spatial filters are then applied to each mechanism. The inverse of the normal spatial model yields now the responses of the colour mechanisms of the normal subject having the same perception than the variant one. The image that would elicit those responses is computed by inverting the normal colour vision model.*

mechanisms. Colour perceptual descriptors are computed from the responses of the final mechanisms.

The examples shown here are restricted to subjects who have either normal colour vision or dichromatic colour vision. We have shown elsewhere [7] that satisfying protanopic and deuteranopic versions of ATD95 can be obtained with the cone-substitution hypothesis (for protanopes, L cones contain the M pigment and for deuteranopes M cones contain the L pigment, the other cones being normal) if besides the red-green mechanism, which losses its opponency, is nulled. Nulling the S cones (cone-null hypothesis) and the yellow-blue mechanism we obtain a good tritanopic model.

As for the spatial vision model, for simplicity, we have considered a set of three linear filters, one for each of the perceptual mechanisms of the colour vision model. These filters are the observer's contrast sensitivity functions (CSFs), as measured psychophysically with sinusoidal gratings isolating each mechanism [9]. The achromatic filter is band-pass peaking around 4 cpd and with a cut-off frequency at approximately 50 cpd, the chromatic red-green and blue yellow filters are low-pass with cut-off frequencies at approximately 14 and 6 cpd, respectively. The achromatic band-pass filter was implemented as a difference of two Gaussians, and the chromatic low-pass filters are gaussians peaking at the origin. Variant subjects were simulated by changing both the amplitude (maximum sensitivity) and the cut-off frequency (resolution) of either the red-green of the blue-yellow spatial CSFs. (see Figure 2 for an example). We assumed that the angular size of the images (256x256) was 4º. With all this, an image **S**(x,y), that for a normal subject, simulates how an image **T**(x,y) appears to a variant subject, is obtained as follows:

$$\mathbf{S}_{n,i}(x,y) = FT^{-1}\left(FT\left(\mathbf{T}_{v,i}(x,y)\right)\frac{CSF_{v,i}\left(f_x,f_y\right)}{CSF_{n,i}\left(f_x,f_y\right)}\right) \qquad (3)$$

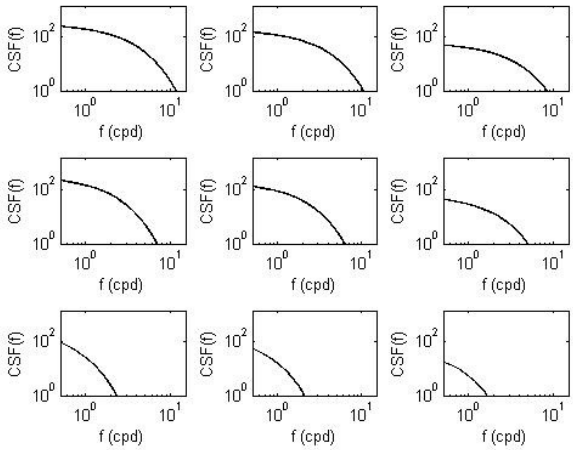

Figure 2. *Alterations in the CSF of the T mechanism studied in this work. Intact CSF, up-left. Overall sensitivity (rows) and cut-off frequency (columns) have been reduced in linear steps. Similar changes were introduced in D. Normal aging and different pathologies produce this kind of changes in contrast sensitivity. Note that scaling of the normal CSF is arbitrary, but that as only the CSF_v to CSF_n ratio is relevant, this is not a problem.*

where *FT* means Fourier Transform and sub-index *i* refers to one of the three mechanisms (i=A,T,D). Subindexes *n* and *v* indicate whether responses and CSFs correspond to the normal or variant subjects. Note that although the values of $\mathbf{p}_{nc}$ and $\mathbf{p}_{vc}$ are not made explicit in this equation, $\mathbf{p}_{ns}$ and $\mathbf{p}_{vs}$ are simply $CSF_{n,i}(f_x f_y)$ and $CSF_{v,i}(f_x f_y)$, respectively. This equation is a straightforward extension to three-dimensional colour space of the algorithm proposed by de Fez et al. [10].

Results

Figures 3-4 shows, as an example, how a subject with normal colour vision would perceive a given image, when either the red-green (Figs. 3) or the blue-yellow (Fig. 4) mechanism present alterations in the corresponding CSFs: for the variant red-green mechanism, the CSF are those of Fig.2; equivalent reductions are introduced in the yellow-blue mechanism. As the gravity of the defect increases, the image palette becomes restricted to yellows and blues for damage in the red-green mechanism (Fig. 3), and to bluish-greens and purples for damage in the blue-yellow mechanism (Fig. 4). No defocus appears, however, since the achromatic mechanism is intact in this example.

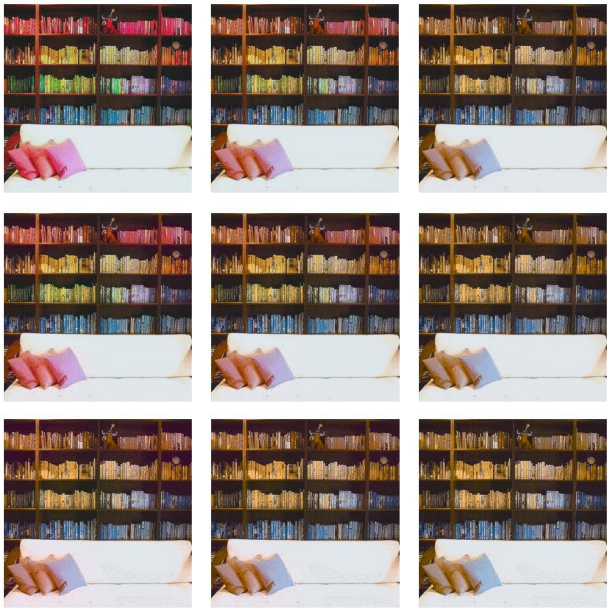

Figure 3. *Alterations in the red-green mechanism. We show the scene in the upper-left corner, as appears, according to Equation (3), to subjects with normal spectral sensitivities in their chromatic mechanisms, but with the alterations in CSF_T described in Figure 2.*

The presence of alterations in the spatial CSF of one of the chromatic mechanisms makes the perception of the subject similar to that of red-green or blue-yellow detectives (Fig. 5), again with intact achromatic mechanisms. Note that although the images corresponding to alterations in spectral sensitivity or in contrast sensitivity in the colour mechanisms (dichromatic subjects), have the same colour palette, they do not coincide pixel to pixel, since parameters $\mathbf{p}_{nc}$ and $\mathbf{p}_{vc}$ in Equation 2 are identical when the subject has normal colour vision, but not in the case of dichromats.

As an example of a subject with alterations both in spectral and contrast sensitivities, Figure 6 displays simulations for a protanopic subject (that is, a subject deprived of the red-green mechanism and with changes in sensitivity of the remaining mechanisms) when the spatial CSF of the yellow-blue mechanism is altered as for the subject in Figure 4. Note that as the gravity of the defect increases, the image becomes achromatic. In this case the original image is not shown: the image in the upper-left corner corresponds to the dichromat with intact CSFs. For a tritanopic observer, similar results would be obtained for alterations in the remaining red-green mechanism (not shown).

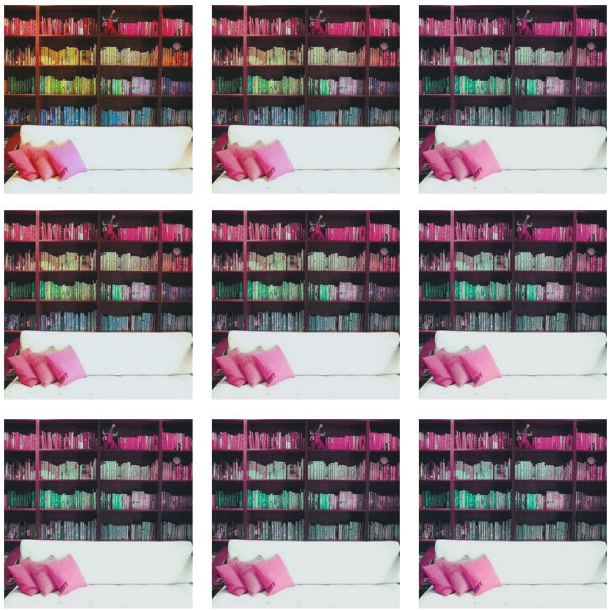

Figure 4. *Alterations in the blue-yellow mechanism. We show the scene in the upper-left corner, as appears, according to Equation (3), to subjects with normal spectral sensitivities in their chromatic mechanisms, but with the alterations in CSF_D. The reductions in overall sensitivity and cut-off frequency have been generated with the same steps than in Figure 2.*

Figure 5. *Subject with normal cone-sensitivities (left) compared with dichromats, when one of the chromatic mechanisms is missing (T up, D down). The images do not coincide point to point, though the colour palettes do.*

Finally, in Figure 7 we may see a more realistic case, a simulation of the perception of a subject whose mechanisms we

have assumed to have intact spectral sensitivities, but altered CSFs, with reductions in the three mechanisms, both in overall sensitivity and cut-off frequency, so as to mimic the behaviour of the subject reported by Sakai and co-workers [9]. Ocular media are assumed to be clear, and therefore the mean luminance value of the image is maintained. Note that both defocus and loss of sensitivity for chromatic differences are present in the simulated image.

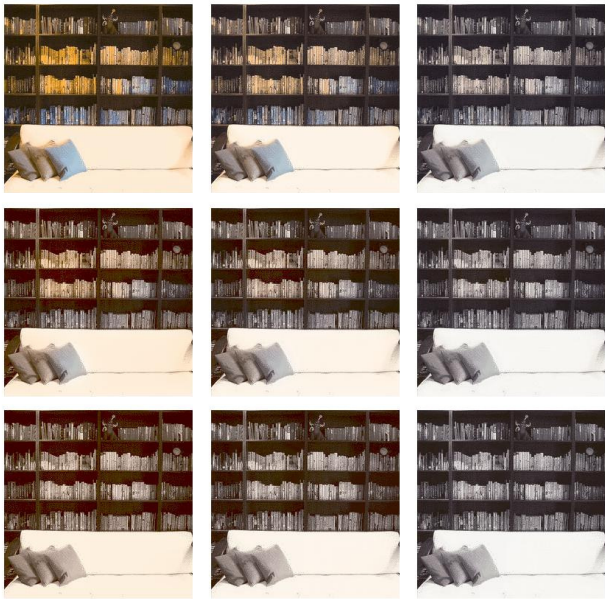

Figure 6. *Protanopic subject with alterations in contrast sensitivity of the sole remaining chromatic mechanism (D). Overall sensitivity and cut-off frequency have been reduced as in the subject of Figure 4.*

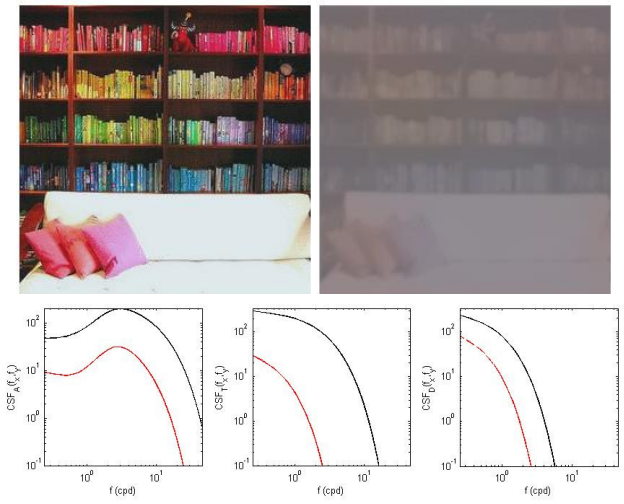

Figure 7. *Up left, original image; up right, simulation of the perception of a subject with intact spectral sensitivities in the ATD mechanisms and transparent ocular media, but reduced contrast sensitivities. The CSF vs. frequency curves show the CSFs of normal subjects in black and those of the variant subject in red. CSFs adapted from Saki et al. [9].*

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