Biological Neural Architecture for Chromatic Adaptation Resulting in Constant Color Sensations *

Torsten Pomierski and Horst Michael Gross

Technical University of Ilmenau

Fachgebiet Neuroinformatik

D-98684 Ilmenau. p.o.box 0565, Germany

phone: +49 3677 69 2858, fax: +49 3677 69 1665

e-mail: pomi@informatik.tu-ilmenau.de

ABSTRACT

A multi-stage color model (De Valois, 1993) was modified and extended to a color appearance model of parvocellular foveal color vision realizing a chromatic adaptation inside a physiologically motivated fundamental color space. This results in prediction of color appearance of object colors under various states of adaptation. During the observation of a plurality of scenes the model is endeavoured to move toward a steady state color-context independent. By this way an average level of color sensation synonymous with constant color sensations is achieved.

1. Introduction

Color is exclusively a matter of perception by the observer. In general the environment has no color. It is composed of colorless matter and energy. The cause of sensation is usually a stimulation, resulting in a psychological process of the organ of sense in question. This leads to sensation as a psychological process. In case of color, the stimulus is the light, reflected from an object, penetrating the eye and triggering the process of color sensation (Fig. 1).
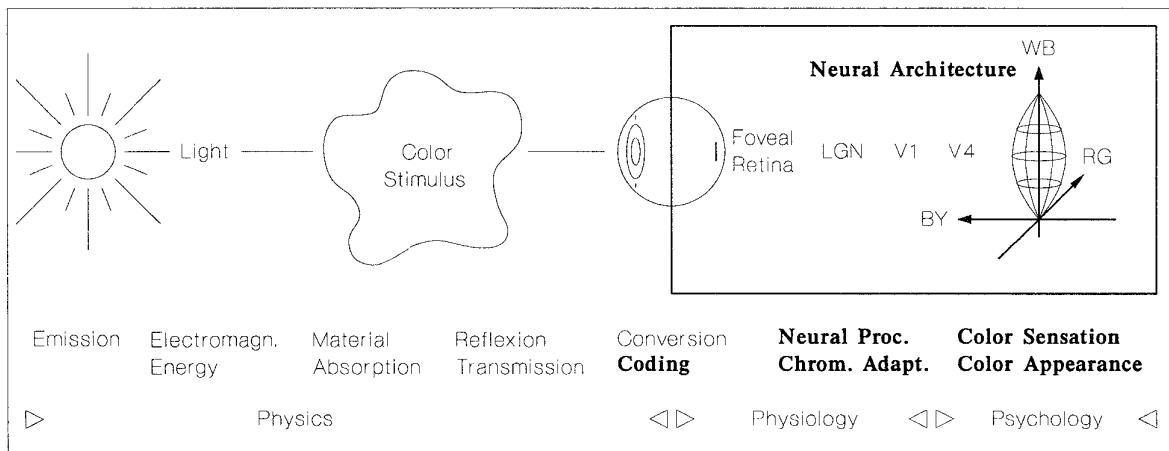

Fig. 1: The impact chain between light and color sensation starts in the field of physics, goes through the field of physiology and finishes in the field of psychology (Extended after Küppers, 1987).

There are two reasons for the extraordinary difficulties in describing the relations between color stimulation and sensation:

- a unique stimulus, i.e. a special physical radiation, generates different sensations of color, and
- different stimuli may lead to the same color sensation.

The basic idea behind is the design of the visual system to perceive differences, rather than inducing a sensation in determined correlation to the stimulus. Therefore, the sensation of color, provoked by exclusive observation of an individual scene over long time, depends on the overall situation in the visual field marked by the number and type of surrounding colors. In order to reach stable colors the dependency of color sensation upon the context of a scene is reduced in case of observing a plurality of natural scenes.

2. Chromatic adaptation and color constancy

The environment appears to have colors only under sufficient illumination. The daylight is continuously changing its spectrum. It varies depending on daytime, season and the geographic meridian. However the average observer perceives the color of a brown desk always the same regardless of the type of light. In reality the desk reflects totally different wavelengthes in the morning light, the reddish light of a sunset or the yellowish tungsten light. Although easy to believe it is not true, that the color impression of an object is determined by light of certain wavelengthes dominantly reflected from its surface. The human color perception is capable of identifying an object almost independently of the perceived visible wavelength spectrum. The visual system tries to adapt to the spectral composition of the actual illumination by modifying its color perception. Practically it adapts to an average level of sensation. So it is capable to adjust to the actual illumination as well as to the special observation conditions (surrounding colors in the visual field). This way an average level of sensation is accomplished and the system guarantees optimum conditions for color discrimination. Prediction of color appearance of objects in different scenes and under various adapting illuminations is an important base of color machine vision and various related applications. The model proposed in this paper is a modified and extended version of the De Valois and De Valois (1993) three stage model, consisting of three chromatic responses in cones, succeeding in opponent cone activations and opponent color activations in the neural system.

3. Modification of the De Valois model

It goes without saying that the first stage of foveal processing is the absorption of light by cones of different photo pigments. The curves of spectral absorption for these photo pigments are well known today. But the problem is the arbitrary normalization regardless of the radiation distribution in the average daylight. This is contrary to a realistic modelling of foveal connections. Although the spectrum of daylight is not static it is possible to determine the radiation distribution of average daylight. Fig. 2 left shows this radiation distribution. The daylight function was determined by averaging several spectral measurements at different times of the day, different weather conditions and at different locations. It indicates roughly a completely covered sky at noon. The various sharp waves have their origins in the special permeability of the atmosphere for different wavelength in the visible spectrum. Since the color temperature of this type of light is 6,504 K it has been named D_{65}. So the displayed curve describes this standard illumination. If one compares the radiation distribution of the average daylight with the sensitivity spectra of the LMS cones proposed by Judd (1945) an interesting similarity becomes apparent (Fig. 2 bottom left). Obviously a result of evolutionary adaptation this effect has to be incorporated into a correct model. Only the spectral distribution of typical daylight effects a full exploitation of the spectral sensitivity functions of all three types of cones. The result is, that only under these conditions the fundamental color space will be fully exploited. Only these conditions of illumination result in an average sensational level with no need for adaptation. Any other illumination requires an adaptation of color perception in order to normalize the color sensation of the same scene. So, contrary to the De Valois model (De Valois und De Valois, 1993), the origin of our model are slightly modified spectral curves (Fig. 2 bottom left) by Judd (1945) and not the curves of Smith and Pokorny (1975) employed by De Valois. Regardless of the number of involved cone pigments (3, 4 or 5) (Neitz and Jacobs, 1991) we assume to have just three types of cones, the L, M and S cones. In general the ratio of L to M cones in the human foveal retina is assumed to be about 2 : 1. According to Boynton (1986) the estimation of the chrominance signal inside the parvo pathway employs just 50% of the L cones. The model of Lennie et al. (1991) is based on the same assumptions. At variance with the De Valois model the foveal ratio in the parvo path is here assumed to be L : M : S as 6 : 6 : 1.

735

4. Activity coded fundamental color space

The modification of the De Valois model in terms of employed cones and their sensitivity curves marks the capability of the visual system to convert foveal cone signals into red/green (RG), blue/yellow (BY) and white/black (WB) activations of a physiologically motivated, fundamental color space. As simulated in our model (Fig. 2 top left) this transformation is performed by the connection of parvo cells in the retina (cones, horizontal cells, midget bipolar and midget ganglion cells) and of parvo LGN cells in the human brain. This conversion
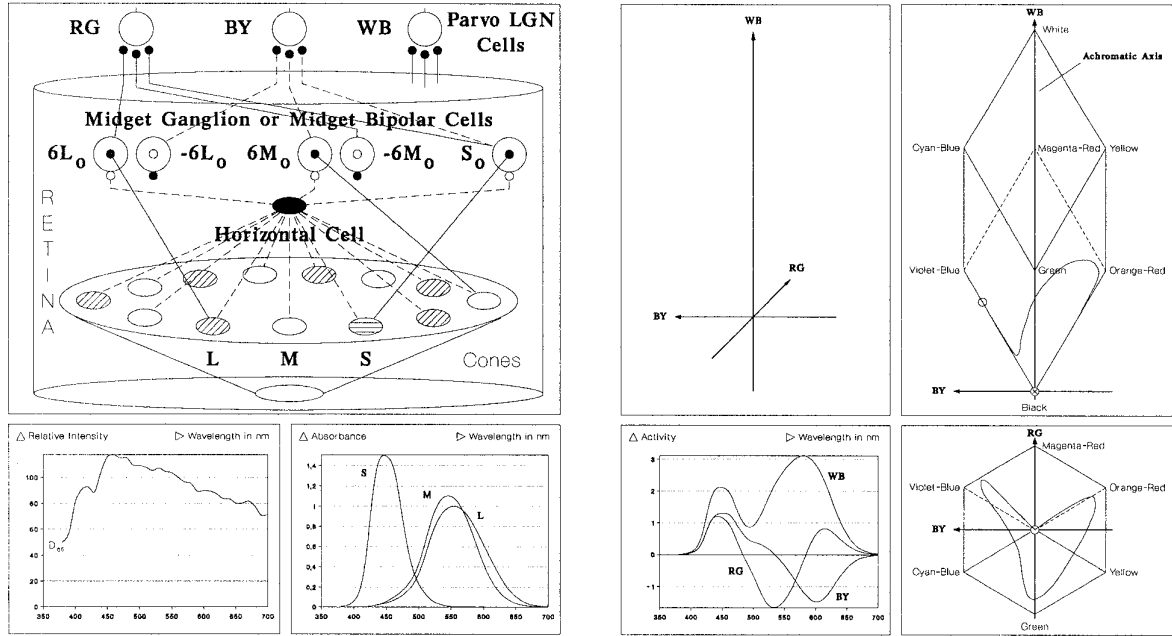

Fig. 2: (bottom left) Comparison of the spectral distribution of typical daylight and spectral sensitivity functions of retinal cones used for simulation (Slightly modified after Judd, 1945). (top left) The connection of retinal and LGN parvo cells underlying the model realizes a transformation of LMS cone sensitivities into opponent RG-, BY- and nonopponent BW activations of parvo LGN cells. (right) The physiologically motivated fundamental color space from side and top view. The bottom panel shows the simulated possible activations of parvo LGN cells in case of sequential stimulation with monochromatic light of different wavelength and its depiction inside the fundamental color space.

can be approximated as linear transformation (De Valois und De Valois, 1993). The resulting space (Fig. 2 top right) is stretched between the orthogonal RG, BY and WB activation axes according to the ideas of Hering (1905) and covers all the color sensations of human being. In order to determine the geometry and the location of an arbitrary color sensation any possible LMS stimulation pattern needs to be transformed.

$$
\begin{pmatrix} RG \\ BY \\ WB \end{pmatrix} = \begin{pmatrix} 72 & -84 & 12 \\ -84 & 72 & 12 \\ 110 & -66 & 19 \end{pmatrix} \begin{pmatrix} L \\ M \\ S \end{pmatrix} ; \qquad \begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} 0,2915 & 0,5909 & 0,1176 \\ 0,1677 & 0,6803 & 0,1520 \\ 0,0 & 0,0549 & 0,9451 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}
$$

Each of these transformed patterns can be illustrated as an RGB pixel on a color monitor. Its position will be defined by the RG, BY and WB activations. In our simulation we used an FCC color monitor. The above described empirically derived transformation enables you to transform FCC norm RGB values into LMS cone activations. The connection of the cells inside the retina and the LGN determines the RG, BY and WB activations and was approximated by a simulatively derived linear transformation. All of the possible RG, BY, and WB activations compose the color space depicted in the right part of Fig. 2. The geometry of the physiological color space shows, that the visual system is capable of having eight extreme color sensations, marked by the corners of the rhomboid. These are black, violet-blue, green, orange-red,

cyan-blue, magenta-red, yellow and white. Based on the resulting geometry of the color space it is possible to extract the following direct linear transformation of RGB values into RG, BY, and WB activations.

$$\begin{pmatrix} RG \\ BY \\ WB \end{pmatrix} = \begin{pmatrix} 0,500 & -1,0 & 0,500 \\ -0,875 & 0,0 & 0,875 \\ 1,500 & 1,5 & 1,500 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix} ; \quad \begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} 0,22 & 0,571 & 0,33 \\ 0,22 & 0,000 & -0,67 \\ 0,22 & -0,571 & 0,33 \end{pmatrix} \begin{pmatrix} RG \\ BY \\ WB \end{pmatrix}$$

Accordingly, the inverse transformation can be described as shown beside. The neurophysiologically motivated fundamental color space, proposed in this article was found to be in excellent conformity with the publication of Küppers (1973). But only our transformation based on a mathematical model of neurobiological connection facilitates you to understand the problematic nature of color-visual defects and opens the gate to the algorithmic implementation of color adaptation and human color appearance. Fig. 2 bottom right displays the simulated possible activations of parvo LGN cells in case of sequential stimulation with monochromatic light of different wavelengthes. It can be observed, that the RG and the BY courses contain considerable negative components. In distinction, the WB plot utilizes only the positive range of activation. It does not correspond to the frequently modeled Photopic Luminosity Function V_λ found in the magno system. This can be explained by the fact that magno and the here analyzed parvo system refer to different neural structures within the visual system. The negative components in both of the other activation plots cover the same area as the positive ones. It follows from this that an achromatic stimulus with D_{65} like spectral intensity results in zero activations for RG and BY. The simulated activations of parvo LGN cells, depicted in Fig. 2 bottom right appear in the fundamental color space just in the lower third (Fig. 2 top right). Except magenta-red, which is not present in the visible spectrum, all the color sensations are activated in the RG/BY plane (Fig. 2 bottom right). Hereby the activation course is closed in the coordinate origin. Yet the simple mapping of monochromatic stimuli into the physiological color space does obviously not result in the expected color sensation of an normally situated observer. This gave rise to the conclusion that normal color appearance after processing within the parvo retina and the parvo LGN must be achieved by an active internal process of dynamic adaptation.

5. Color constancy by an average level of sensation

The basis of the following consideration is an arbitrary signal source (for instance a video camera) amplifying the R, G and B component with a constant ratio, free of overamplification, in absence of white balance and thus providing an image free of overamplification with regards to the three color components (Fig. 3 left). The first processing step is a conversion of topologically dependent RGB values of natural scenes into the fundamental color space by the introduced direct transformation. The transformed pixels of a single image build up a special cluster within the color space (Fig. 3 top right). The position of each of these points is defined by their RG, BY and WB activations. The whole cluster will be elongated from the WB axis (achromatic axis) depending on the illuminative conditions during image acquisition. Since human eye adaptation of intensity ensures cone signals free of overamplification, the cluster will be compressed. The elongation of this cluster characterizes the deviation in illumination from the typical daylight condition regardless of the image contents. Detailed investigations of Bartleson (1979) show interesting correspondences to this effect. His experimental work involved methods of direct scaling applied to a set of test stimuli of different chromaticities seen under different states of adaptation. Each test stimulus was viewed centrally in a surround of high reflectance illumination by one of two sources which provided chromaticities of the surround closely representing those of CIE standard illumination A (2,856 K) and CIE standard illumination D_{65} (6,504 K). The geometric mean data for two groups of test stimuli were plotted on two polar diagrams (Fig. 3 bottom right) in which hues are represented by angles, with the four unitary hues being at right angles and colorfulness arranged radially. It is of interest to state, that one group of test stimuli leading to color appearance under D_{65} adaptation, as depicted in Fig. 3 bottom left, shows, under A adaptation, the same color appearance as a second group of test stimuli under D_{65} adaptation (Fig. 3 bottom right). It becomes obvious that the visual system realizes a restoration of test stimuli, transformed into the fundamental color space, in the form of an elongated cluster into the achromatic WB axis. This process guarantees stable color sensations independent of illumination. An equally distributed average daylight illumination will immediately result in a vertically oriented cluster with no need for chromatic adaptation using the fundamental color space as a whole (Fig. 3 right). A cluster of this

orientation exactly refers to an interpretation of color constancy that has only been postulated so far, but now can be explained by geometric means. There is no further need of modification in order to realize custom color appearance. Under this assumption all of the achromatic color sensations appear at the achromatic axis. For each elongated cluster an exclusive axis can be obtained to be converted into the WB direction by simultaneous rescaling it along this axis. This procedure leads to an automatic and reference free chromatic adaptation of the
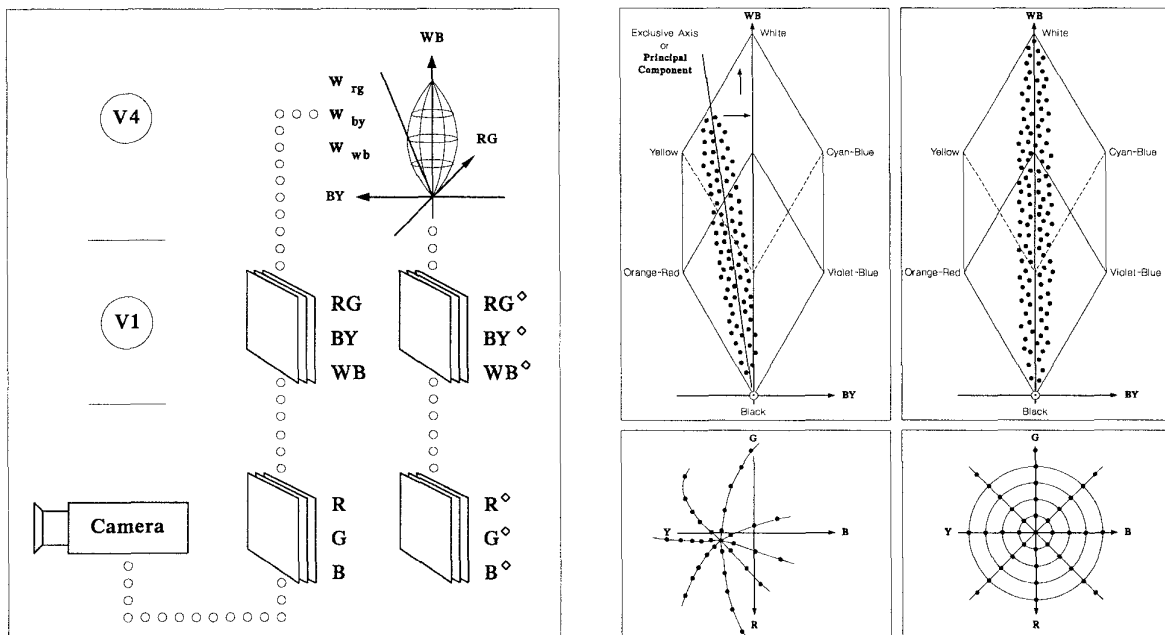

Fig. 3: (left) All topologic pixels of an RGB image are transformed into the fundamental color space by the proposed direct transformation. The positions of the resulting points are coded as RG, BY and WB activations. They are optimized resulting in new $RG^\diamond$, $BY^\diamond$ and $WB^\diamond$ activations by chromatic adaptation. (right) The elongated color transformation cluster in case of nontypical daylight (tungsten light) illumination without chromatic adaptation and conditions of the same cluster after chromatic adaptation by application of the adaptation algorithm. The circles of the bottom left panel (from Bartleson, 1979) indicate the color appearances under D_{65} adaptation that correspond to a set of test stimuli that under A adaptation would have the same color appearances as the corresponding circles of the undistorted graph (bottom right) indicating the color appearance of a second set of test stimuli under D_{65} adaptation.

whole image within the fundamental color space. The extraction of the exclusive axis was performed by a well known learning algorithm (Oja, 1982). To obtain parameters about the elongation of the cluster within the color space the network determines the largest eigenvector e of the autocorrelation matrix $\mathbf{C} = E\{\mathbf{x}\mathbf{x}^T\}$ of the cluster. This way the exclusive axis or principal component is represented by the weight vector w. Its adaptation can be described as follows (Oja, 1982):

$$\mathbf{w} := \mathbf{w} + \gamma \, y \, (\mathbf{x} - y\mathbf{w}) \qquad \text{with} \qquad y = \mathbf{x}^T\mathbf{w}$$

Therein $\mathbf{x} = (RG, BY, WB)^T$ marks the normalized input vector (in interval $< -1, 1 >$) as a position of a point in the fundamental color space, y describes the output activity, $\mathbf{w} = (w_{rg}, w_{by}, w_{wb})^T$ stands for the principal component and γ represents the learning rate. Knowing the principal component w (Fig. 3 left) enables the algorithm to optimize the position of each point in relation to the RG, BY and WB axes.

$$RG^\diamond_{xy} = RG_{xy} - w_{rg} \, \alpha_{Dyn} \, f(WB_{xy}); \quad BY^\diamond_{xy} = BY_{xy} - w_{by} \, \beta_{Dyn} \, f(WB_{xy}) \quad \text{with} \quad f(WB_{xy}) = \frac{WB_{xy}}{w_{wb} \, \gamma_{Dyn}} \quad (1)$$

$$WB^\diamond_{xy} = WB_{min} \, (WB_{xy} - WB_{min}) \frac{WB^\diamond_{max} - WB^\diamond_{min}}{WB_{max} - WB_{min}} \quad (2)$$

RG_{xy}, BY_{xy} and WB_{xy} stands for the incomming and $RG^\diamond_{xy}$, $BY^\diamond_{xy}$ and $WB^\diamond_{xy}$ stands for the chromatically adapted activities of a pixel at the position (x, y) in the scene (Fig. 3 left). By performing the inverse transformation of all

points of the new positioned cluster into RGB space you obtain a chromatically adapted image.

$$\begin{pmatrix} R^\diamond \\ G^\diamond \\ B^\diamond \end{pmatrix} = \begin{pmatrix} 0,22 & 0,571 & 0,33 \\ 0,22 & 0,000 & -0,67 \\ 0,22 & -0,571 & 0,33 \end{pmatrix} \begin{pmatrix} RG^\diamond \\ BY^\diamond \\ WB^\diamond \end{pmatrix}$$

Employing this method to the conversion of an individual scene the result of chromatic adaptation is related to the context of this scene after long time exclusive contemplation, just similar to the biological model. Only the consideration of a plurality of scenes leads to a chromatic adaptation that is context independent and therefore to the usual color appearance in terms of average color sensitivity. This is the final goal to be achieved under any circumstances and at the same time can be interpreted as the reason for color constancy in real live.

6. Conclusion

The here suggested neural mechanism for chromatic adaptation has a sound neuroanatomical base and convincingly explains a lot of psychophysical phenomenons of perception described by various authors (Land, 1983; Hunt, 1979).

The main advantage of the algorithm is the absence of any reference. Furthermore all pixels of a perceived scene equally contribute to the determination of the correction value. The spatial relations of the points inside the cluster remain stable. Therefore no distortion of color information can be observed. In terms of color adaptation the axes of the fundamental color space are optimally decorrelated in space. The geometry of the physiological color space ensures under any circumstances the possibility to determine the relevant principal component. Furthermore the color distortion can be quantified exactly.

The employment of the proposed neural mechanism for color adaptation resulting in usual constant color sensations imposes just one possible field of application among a number of others in color processing.

References

De Valois, R. L. and De Valois, K. K. (1993). A multi-stage color model. *Vision Res.*, **3**, 1053-1065.

Bartleson, C. J. (1979). Changes in color appearance with variations in chromatic adaption. *Color Research and Application*, **4**, 119-138.

Boynton, R. M. (1986). A system of photometry and colorimetry based on cone excitations. *Color Research and Application*, **11**, 245-252.

Hering, E. (1905). Grundzüge der Lehre vom Lichtsinn. In *Handbuch der gesamten Augenheilkunde*. ed. Saemisch, T. Leipzig: Verlag von Wilhelm Engelmann.

Hunt, R. W. B. (1979). Measures of colour appearance in colour reproduction. *Color Research and Application*, **4**, 39-43.

Judd, D. B. (1945). Standard response functions for protanopic and deuteranopic vision. *J. Opt. Soc. Am.*, **35**, 199-220.

Küppers, H. (1973). Color - Origin, system, uses. New York, London, Toronto, Melbourne: Van Nostrand Reinhold Ltd.

Küppers, H. (1987). Farbe: Ursprung - Systematik - Anwendung. München: Callwey.

Land, E. H. (1983). Recent advances in retinex theory and some implications for cortical computations: Color vision and the natural image. *Proc. Natl. Acad. Sci. USA*, **80**, 5163-5169.

Lennie, P., Haake, P. W. and Williams, D. R. (1991). The design of chromatically opponent receptive fields. In *Computational models of visual processing*. eds. Landy, M. S. and Movshon, J. A. pp. 71-82. Cambridge, Mass.: MIT Press.

Neitz, M., Neitz, J. and Jacobs, G. H. (1991). Spectral tuning of pigments underlying red-green color vision. *Science*, **252**, 971-974.

Oja, E. (1982). A simplified neuron model as a principal component analyzer. *J. Math. Biology*, **15**, 267-273.