Analysing the color uniformity of the ATTD05 perceptual space

Elísabet Chorro, Francisco Miguel Martínez-Verdú*, Dolores de Fez*, Pascual Capilla** and Maria José Luque***

**Departamento de Óptica, Farmacología y Anatomía. Universidad de Alicante*
Carretera de San Vicente del Raspeig s/n.
03690 Alicante (Alicante, Spain)

***Departament. d'Òptica. Facultat de Física. Universitat de València*
Dr. Moliner, 50.
46100 Burjassot (València, Spain)

Abstract

The aim of this work is to study the uniformity of the perceptual space of the multistage neural colour vision model ATTD05 by comparison with CIECAM02, which is the latest colour appearance model adopted by the CIE. A set of parameters describing the deformation suffered by the loci of constant chroma and hue of the Munsell Atlas, were used to measure the degree of uniformity of the space. From these results we can conclude that ATTD05 is, in general, more uniform as CIECAM02.

Introduction

Colour vision models try to predict perceptual descriptors of colours under different viewing conditions. There are two main types of colour vision models: colour appearance models [1-7] and neural models [8-17]. Both predict perceptual descriptors, but differ in that neural models also try to follow the stages of the visual system. However, quite often evaluating colour differences between two samples is more important than obtaining numerical values of perceptual descriptors. Over the years, specific models have been developed to fit colour difference data [19-22], but the perfect solution would be to obtain a single model, which could reproduce both perceptual descriptors and colour differences. And if the colour space is uniform, the computation of colour differences becomes easier. In particular, if uniformity results are satisfactory, we mean to use with ATTD05 the procedure followed by Luo et al. [21,22] to obtain a colour difference formula for CIECAM02 [20], the latest colour appearance model adopted by the CIE.

Firstly, in this paper we briefly describe the neural model, ATTD05. After that, we study the uniformity of the perceptual space of the model. For that, we compare the uniformity of the perceptual space of ATTD05 with the uniformity of CIECAM02 -the latest colour appearance model adopted by the CIE- by representing some Munsell samples in these spaces and checking whether they are uniformly spaced, as they should. The uniformity test is the deformation suffered by the loci of constant chroma and hue of the Munsell Atlas. A set of 8 parameters were used to measure the degree of uniformity of the space.

Description of the ATTD05 model

ATTD05 [23,24] is a neural model that tries to predict perceptual descriptors of colours under different viewing conditions, following the stages of visual system. This multistage colour vision model has been developed by Capilla, Gómez & Luque (from the University of Valencia) for the last years. A schema of the model appears in Figure 1.

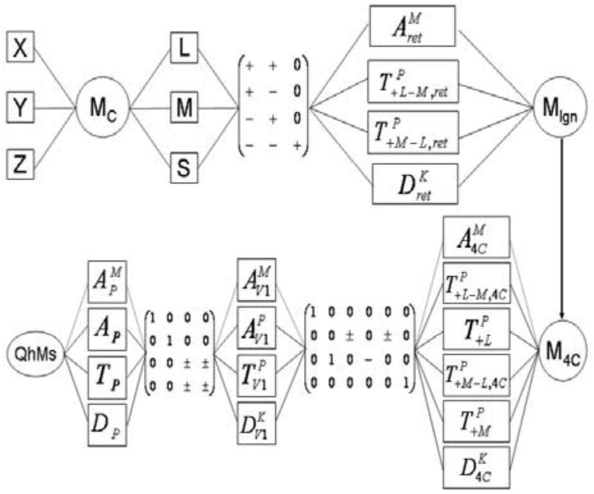

Figure 1. *Schema of the ATTD05 model. Pre-cortical and cortical stages*

The ATTD model computes the perceptual descriptors of an object from its XYZ tristimulus values and those of its background. The gain-controlled cone-responses are combined, yielding an achromatic channel, mediated by Magno cells with Type III receptive fields, and three opponent channels: two with red-green opponency but different polarities, mediated by Parvo cells with Type I receptive fields, and one with blue-yellow opponency, mediated by Parvo cells with Type II receptive fields. These three opponent channels, after two opponent transformations at cortical level, generate the achromatic, red-green and blue-yellow perceptual mechanisms. The first opponent stage simulates the synapsis between the LGN cells and cells in layer 4Cβ. We admit that the same cell classes exist in the LGN and 4Cβ and that this stage does not modify the LGN signals. The simulated responses of the 4Cβ cells are subsequently combined to yield an achromatic and two chromatic (one red-green and one blue-yellow) intermediate channels. The responses of these channels to the object are modified by the responses to the background by means of a subtractive process. This stage would be mediated by Type III and double-opponent cells in layers 2 and 3. Finally, the responses of these intermediate mechanisms are combined to generate the responses of the perceptual mechanisms, from which we compute descriptors for brightness, hue, colourfulness and saturation.

Uniformity of the perceptual space of the ATTD05 model

Firstly, we compare the uniformity of the perceptual space ATTD05 with the uniformity of CIECAM02. To do that, we use perceptually equally spaced samples from the Munsell Atlas and test if they appear to be also uniformly spaced in the perceptual space of the model. We have chosen samples from the Munsell Atlas with constant values, 3, 5 and 7. As can be seen in Figure 2, both CIECAM02 and ATTD05 seem quite uniform under this test.

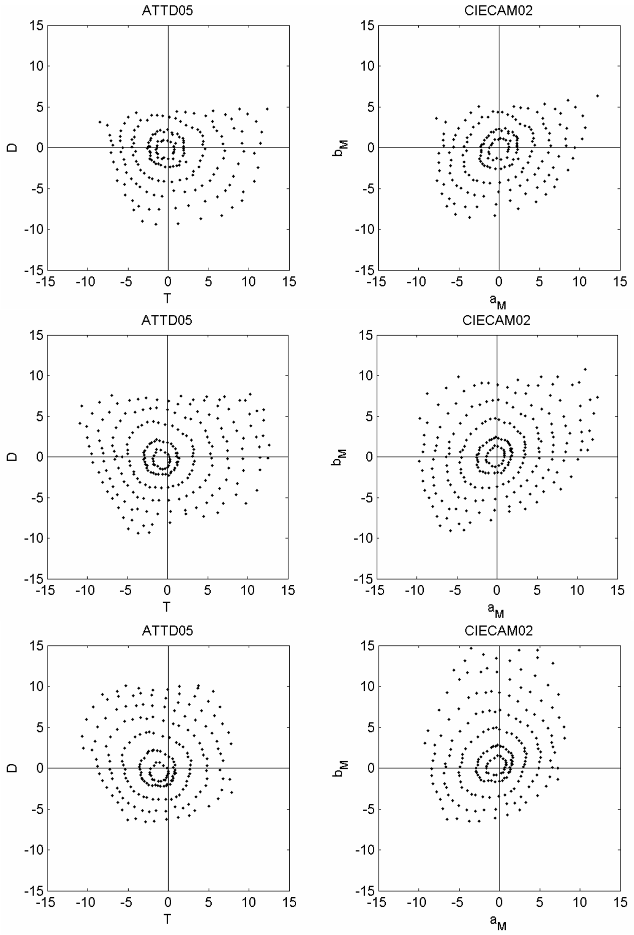

Figure 2. *Samples of constant Munsell Value (3, 5 and 7, respectively) plotted on the perceptual plane of the ATTD05 and CIECAM02 models*

Particularly, the rings in ATTD05 look more circular. However we can see that the centre of the rings is a bit out of place. But those observations are only qualitative. A set of 8 parameters were used to quantify how much the loci differ from equally spaced chroma rings and angularly equally space hue lines. These parameters were:

- the position of the centre of gravity, $TD(C_0)$
- the mean radius of the Chroma C_M ring for Value V, $R_{V,CM}$
- the circularity index of the C_M Chroma ring for Value V, $\varepsilon_{V,CM}$
- the Chroma spacing index, $\varepsilon_{V,R}$
- the hue spacing index $\varepsilon_{H,V,CM}$
- the position of the centre of gravity of the Chroma C_M ring for Value V, $TD(C_{0,CM})$
- the eccentricity index of the Chroma C_M ring for Value V, $ev(C_{0,CM})$
- the dispersion index of the centres of gravity, $\varepsilon_{V,e}$

Definitions of the uniformity parameters

Munsell Chromas and Values of the samples will be specified, when necessary, by subscripts C_M and V, respectively. For comparison purposes, the values of T_p and D_p and their equivalents in CIECAM02 model (a_M, b_M) were normalized, for each Value, in such a way that the mean distance between the samples of the Munsell Chroma 6 locus to their own "centre of gravity" is six. That is, for any colour C_i of the Munsell Atlas, with perceptual descriptors $TD_P(C_i) = [T_P(C_i), D_P(C_i)]$ in the chromaticity plane, the normalized descriptors $TD(C_i) = [T(C_i), D(C_i)]$ are defined as follows:

$$TD(C_i) = \frac{6}{R_{V,C_M=6}} \cdot TD_P(C_i) \tag{1}$$

where the mean radius of the Munsell Chroma 6 ($C_M = 6$) ring for the V value considered, $R_{V,CM=6}$, is given by:

$$R_{V,C_M=6} = \frac{1}{N_{V,C_M=6}} \cdot \sum_{j=1}^{N_{V,C_M=6}} \left\| TD_P\left(C_{j,C_M=6}\right) - TD_P\left(C_{0,C_M=6}\right) \right\| \tag{2}$$

$N_{V,CM=6}$ is the number of samples, $C_{i,CM=6}$, in the Chroma 6 ring for the considered value, and $TD_P(C_{0,CM=6})=[T_P(C_{0,CM=6})\ D_P(C_{0,CM=6})]$ is the vector defining its "centre of gravity", $C_{0,CM=6}$, that is:

$$TD_P(C_{0,C_M=6}) = \frac{1}{N_{V,C_M=6}} \cdot \sum_{j=1}^{N_{V,C_M=6}} TD_P\left(C_{j,C_M=6}\right) \tag{3}$$

For each Munsell Value, the centre of gravity, $TD(C_0)$, of the normalised TD descriptors is computed with Equation A.4:

$$TD(C_0) = \frac{1}{N_V} \cdot \sum_{j=1}^{N_V} TD\left(C_j\right) \tag{4}$$

where N_V is the total number of samples C_j for the Value V. The radius of all the samples corresponding to that Value are calculated as distances to this centre:

$$R\left(C_j\right) = \left\| TD\left(C_j\right) - TD\left(C_0\right) \right\| \tag{5}$$

Circularity, Chroma-spacing and hue-spacing

The mean radius, $R_{V,CM}$, and the circularity index, $\varepsilon_{V,CM}$, of each Chroma ring are computed as follows:

$$R_{V,C_M} = \frac{1}{N_{V,C_M}} \cdot \sum_{j=1}^{N_{V,C_M}} R\left(C_j\right) \tag{6}$$

$$\varepsilon_{V,C_M} = \frac{1}{N_{V,C_M}} \cdot \sum_{j=1}^{N_{V,C_M}} \left(R\left(C_j\right) - R_{V,C_M}\right)^2 \tag{7}$$

We introduce the Chroma spacing coefficient, $\varepsilon_{V,R}$, to measure to which degree the rings of Munsell Chroma, $C_{M,i}$, are uniformly spaced at a given constant Munsell Value. It is computed as follows:

$$\varepsilon_{V,R} = \frac{1}{n_{V,C_M}} \cdot \sum_{j=1}^{n_{V,C_M}} \left(\frac{R_{V,C_{M,j}} - C_{M,j}}{C_{M,j}} \right)^2 \tag{8}$$

where $n_{V,CM}$ is the number of Chroma rings used to compute the coefficient for a given Value.

The uniformity of the hue-spacing in a given Chroma locus is evaluated by means of the hue spacing index, $\varepsilon_{H,V,CM}$, defined as follows:

$$\varepsilon_{H,V,C_M} = \frac{1}{N_{V,C_M}} \cdot \sum_{j=1}^{N_{V,C_M}} \left(\frac{\Delta H\left(C_j\right)}{R\left(C_j\right)} - \frac{2\pi}{N_{V,C_M}} \right)^2 \tag{9}$$

where:

$$\Delta H\left(C_j\right) = \left\| TD\left(C_j\right) - TD\left(C_{j+1}\right) \right\| \tag{10}$$

Note that $\Delta H(C_i)$ is not a hue increment, but the distance between two consecutive hues measured in the normalized TD plane. In incomplete rings $\Delta H(C_i)$ and $\varepsilon_{H,V,CM}$ are redefined to avoid regions where hues are missing.

Eccentricity and stability

The eccentricity of the constant Munsell Chroma loci were evaluated by means of the ring's centre eccentricity, $e_V(C_{0,CM})$, measured from the global "centre of gravity" for that value, that is:

$$e_V\left(C_{0,C_M}\right) = \left\|TD\left(C_{0,C_M}\right) - TD\left(C_0\right)\right\| \qquad (11)$$

where $TD(C_{0,CM})$ is the centre of gravity of the Chroma C_M ring for value V, defined as follows:

$$TD\left(C_{0,C_M}\right) = \frac{1}{N_{V,C_M}} \cdot \sum_{j=1}^{N_{V,C_M}} TD\left(C_{j,C_M}\right) \qquad (12)$$

Finally, to quantify the stability of the centres of gravity for Munsell Value V, we use a coefficient $\varepsilon_{V,e}$, given by:

$$\varepsilon_{V,e} = \frac{1}{n_{V,C_M}} \cdot \sum_{j=1}^{n_{V,C_M}} e_V\left(C_{0,C_M}\right)^2 \qquad (13)$$

A perfectly uniform space requires the circularity index, the chroma and hue spacing indexes and the dispersion index of the gravity centres to be zero. The lower these values, the more uniform is the space.

The parameters for the Munsell samples with 3, 5 and 7 Value constant calculated with ATTD05 and CIECAM02, under illuminant C, are shown in Tables I and II, respectively (we only have used Chroma rings containing all hues).

Table I. Parameters to assess the uniformity of the perceptual plane of ATTD05 space using Munsell samples

Value	C	$T(C_0)$	$D(C_0)$	$R_{V,CM}$	$\varepsilon_{V,CM}$	$100\varepsilon_{V,R}$	$\varepsilon_{H,V,CM}$	$T(C_{0,CM})$	$D(C_{0,CM})$	$e_V(C_{0,CM})$	$\varepsilon_{V,e}$
3	1	-0.17	-0.29	1.19	0.03	1.56	0.23	-0.39	-0.24	0.23	0.13
	2			2.28	0.03		0.19	-0.29	-0.15	0.19	
	4			4.28	0.09		0.19	-0.22	-0.03	0.27	
	6			6.03	0.34		0.24	0.17	-0.79	0.60	
5	1	-0.68	-0.10	1.14	0.04	0.59	0.21	-0.71	-0.44	0.34	0.18
	2			2.14	0.02		0.20	-0.78	-0.23	0.17	
	4			4.16	0.11		0.19	-0.85	0.06	0.23	
	6			6.00	0.20		0.21	-0.73	0.25	0.35	
	8			7.68	0.35		0.21	-0.67	0.30	0.40	
	10			9.16	0.79		0.23	-0.28	-0.76	0.77	
7	1	-1.27	0.05	1.28	0.14	1.89	0.38	-1.06	-0.64	0.72	0.20
	2			2.22	0.02		0.21	-1.21	-0.33	0.38	
	4			4.17	0.07		0.20	-1.34	0.02	0.07	
	6			6.00	0.19		0.21	-1.34	0.30	0.26	
	8			7.60	0.51		0.20	-1.29	0.54	0.50	

Table II. Parameters to assess the uniformity of the perceptual plane of CIECAM02 space using Munsell samples

Value	C	$T(C_0)$	$D(C_0)$	$R_{V,CM}$	$\varepsilon_{V,CM}$	$100\varepsilon_{V,R}$	$\varepsilon_{H,V,CM}$	$T(C_{0,CM})$	$D(C_{0,CM})$	$e_V(C_{0,CM})$	$\varepsilon_{V,e}$
3	1	-0.05	-0.09	1.32	0.04	3.66	0.24	0.00	-0.07	0.06	0.06
	2			2.39	0.05		0.20	0.03	-0.01	0.12	
	4			4.34	0.10		0.21	-0.09	0.16	0.26	
	6			6.02	0.27		0.26	-0.13	-0.49	0.41	
5	1	-0.41	0.47	1.24	0.12	1.27	0.30	-0.09	0.09	0.50	0.18
	2			2.20	0.10		0.22	-0.19	0.21	0.34	
	4			4.13	0.11		0.21	-0.36	0.45	0.06	
	6			6.01	0.19		0.22	-0.44	0.76	0.28	
	8			7.80	0.40		0.22	-0.60	1.06	0.61	
	10			9.24	0.60		0.25	-0.65	0.04	0.50	
7	1	-0.57	0.81	1.29	0.13	2.02	0.44	-0.25	0.27	0.62	0.19
	2			2.23	0.09		0.22	-0.37	0.46	0.40	
	4			4.15	0.15		0.21	-0.57	0.69	0.11	
	6			6.00	0.24		0.22	-0.70	0.98	0.21	
	8			7.72	0.40		0.21	-0.81	1.36	0.60	

Results

The centre of gravity, TD(C_0), for Munsell Value 3, in ATTD05, is shifted from the origin three times more than in CIECAM02. The displacements are in the same order for the rest of the values (See columns 3 and 4 in Tables I and II)

In Figures 3, 4 and 5, we show the circularity indexes for the three tested Values. The rings of constant Chroma in ATTD05 are, except for the highest Chroma at each Value, more circular than in CIECAM02.

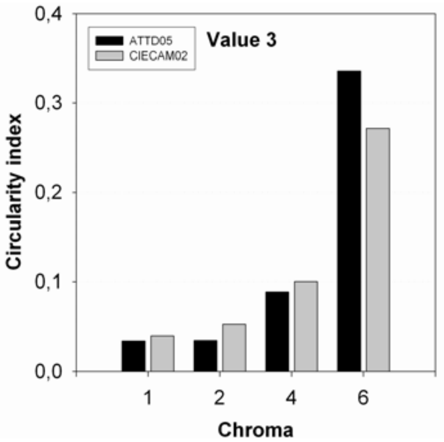

Figure 3. *Circularity index for the different Chroma rings and Value 3.*

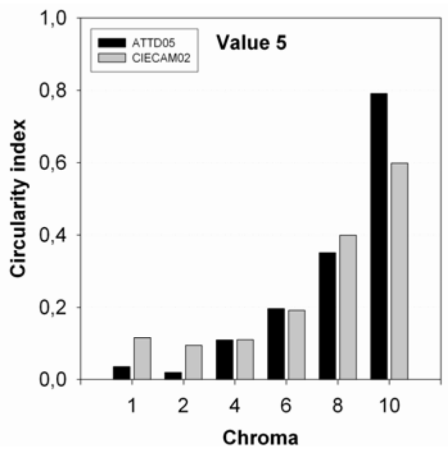

Figure 4 *Circularity index for the different Chroma rings and Value 5.*

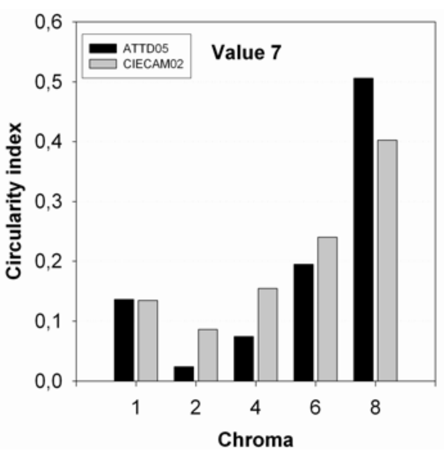

Figure 5. *Circularity index for the different Chroma rings and Value 7.*

ATTD05 does improve the Chroma spacing index too, for all Values, which is represented in the Figure 6.

The hue spacing indexes shown in Figures 7, 8 and 9 for the three Values, are lower in ATTD05 than in CIECAM02, for all Chromas at all Values.

Finally, the eccentricities of the centres of gravity are represented in Figures 10, 11 and 12 for all Chromas at the three Values. Although some eccentricities are greater and some lower, the global dispersion index (see Figure 13), which is the relevant parameter quantifying the stability of the centres of gravity of the rings, for a given Value, is worst in ATTD05 than in CIECAM02 for Value 3, but is in the same order for the rest of the Values.

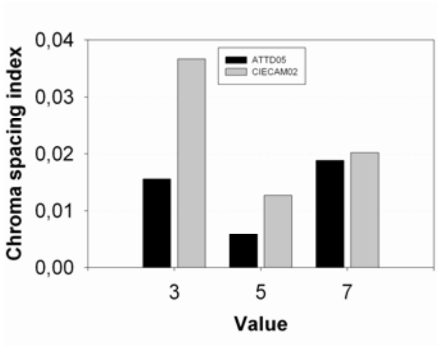

Figure 6. *Chroma spacing index for the different Values*

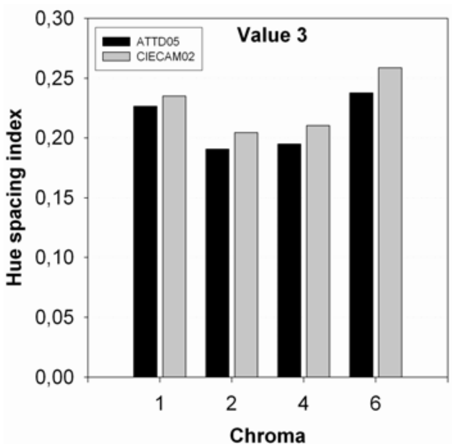

Figure 7. *Hue spacing index for the different Chroma rings and Value 3*

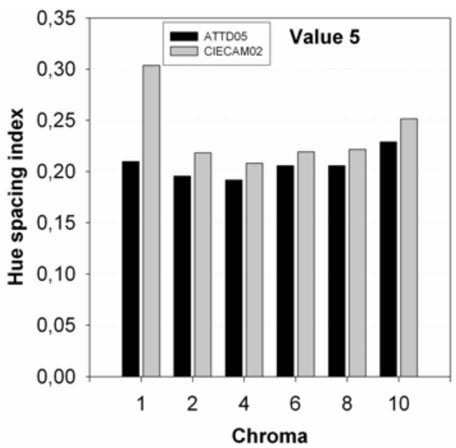

Figure 8. *Hue spacing index for the different Chroma rings and Value 5*

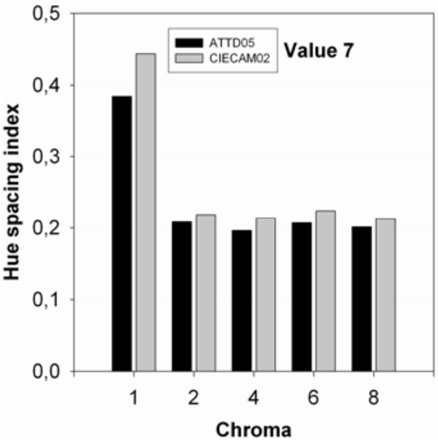

Figure 9. *Hue spacing index for the different Chroma rings and Value 7*

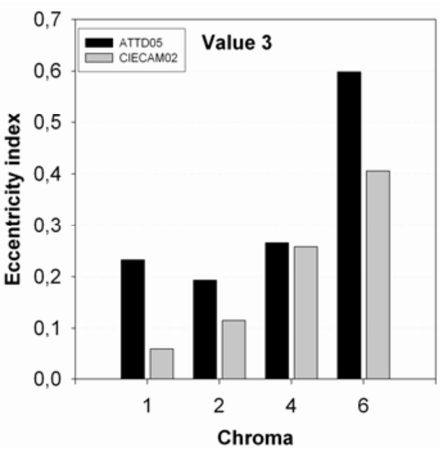

Figure 10. *Eccentricity index for the different Chroma rings and Value 3*

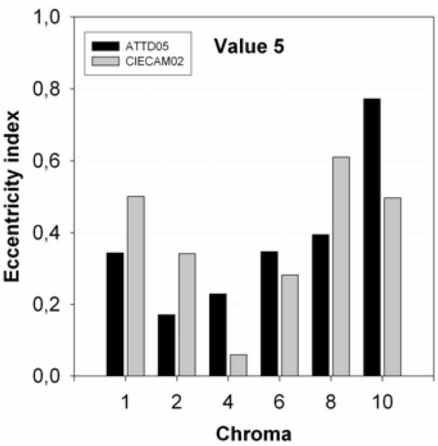

Figure 11. *Eccentricity index for the different Chroma rings and Value 5*

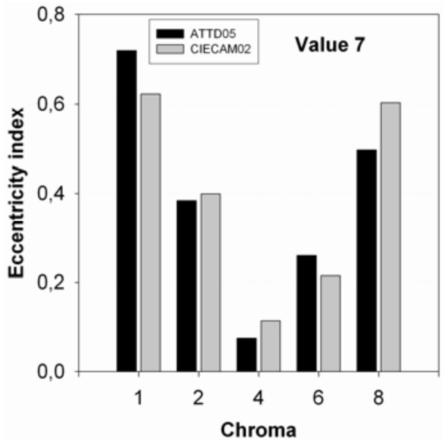

Figure 12. *Eccentricity index for the different Chroma rings and Value 7*

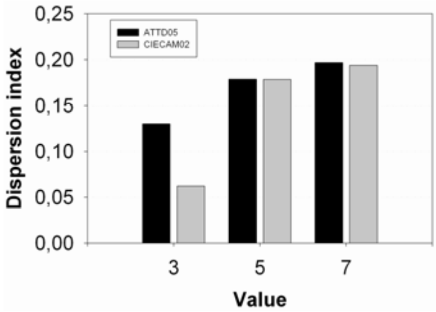

Figure 13. *Dispersion index for the different Values.*

Conclusions

Since the locus of constant Chroma are more circular (with one exception), the Chroma spacing indexes for all Values and the hue spacing indexes for all Chromas and Values are also lower, and the eccentricity of the centre of gravity for a given Value and the corresponding index of dispersion of the centres of gravity for the rings of the population for that Value are in the some order (again with few exceptions), we conclude that the perceptual space of ATTD05 has a higher degree of uniformity than that of CIECAM02. Consequently, a useful colour difference formula can be implemented [25].

References

[1] R.W.G. Hunt, Revised colour-appearance model for related and unrelated colours. Col. Res. Appl., 16, 146-165 (1991).

[2] R.W.G. Hunt, An improved predictor of colourfulness in a model of colour vision. Color Res. Appl. 19, 23-26, (1994).

[3] M.D. Fairchild and R.S. Berns, Image color-appearance specification through extension of CIELAB. Color Res. Appl. 18, 178-190 (1993).

[4] M.D. Fairchild, Refinement of the RLAB color space. Color Res. Appl. 21, 338-346 (1996).

[5] M.R. Luo, M.C. Lo and W.G. Kuo, The LLAB(l:c) colour model. Color Res. Appl. 21, 412-429, (1996).

[6] Y. Nayatani, K. Hashimoto, K. Takahama and H. Sobagaki, A non-linear color-appearance model using Estévez-Hunt-Pointer primaries. Col. Res. Appl., 12, 231-242, (1987).

[7] Y. Nayatani, K. Takahama, H. Sobagaki and K. Hashimoto, Color-appearance model and chromatic-adaptation transform. Color Res. Appl., 15, 210-221 (1990).

[8] R.M. Boynton, A system of photometry and colorimetry based on cone excitations. Color Res. and Appl., 11, 244-252 (1986)
[9] R.L. De Valois and K.K. De Valois, A multi-stage color model. Vision Res., 33, 1053-1065 (1993).
[10] R.L. De Valois and K.K. De Valois, E. Switkes, M. Luke, Hue scaling of isoluminant and cone-specific lights. Vision Res., 37, 885-897 (1997).
[11] S.L. Guth, R.W. Massof and T. Benzschawel, Vector model for normal and dichromatic vision. J. Opt. Soc. Am. 70, 197-212 (1980).
[12] S L. Guth, Model for color vision and light adaptation. J. Opt. Soc. Am. A, 8, 976-993 (1991). Erratum. J. Opt. Soc. Am. A, 9, 344 (1992).
[13] S.L. Guth, Unified model for human color perception and visual adaptation II. Proc. SPIE- The International Society for Optical Engineering, 1913, 440-448 (1993).
[14] S.L. Guth, ATD model for color vision I: background. Proc. SPIE- The International Society for Optical Engineering, 2170, 149-152, (1994).
[15] S.L. Guth, ATD model for color vision II: applications. Proc. SPIE- The International Society for Optical Engineering, 2170, 153-162 (1994).
[16] S.L. Guth, Further applications of the ATD model for color vision. Proc. SPIE- The International Society for Optical Engineering, 2414, 12-26 (1995).
[17] A. Valberg, T. Seim, B.B. Lee and J. Tryti, Reconstruction of equidistant color space from responses of visual neurones of macaques. J. Opt. Soc. Am., A, 3, 1726-1734, (1986).
[18] M.R. Luo, R.W.G. Hunt, The structure of the CIE 1997 colour appearance model (CIECAM97s). Color Res Appl 1998; 23, 138-146.
[19] CIE. Industrial colour difference evaluation. CIE Publ. 116, 1995.
[20] CIE. A Colour Appearance Model for Colour Management Systems: CIECAM02. CIE Publ. 159, 2004.
[21] M.R. Luo, C. Li and G. Cui, Combining Colour Appearance model with Colour Difference Formula. The 10th Congress of the International Colour Association (AIC'05) 8-13 May, Granada, Spain, 2005. pg 235-240.
[22] M.R. Luo, G. Cui and C. Li. Uniform Colour Spaces Based on CIECAM02 Colour Appearance Model. Color Res Appl 2006; 31, 4:320-330.
[23] J. Gómez-Chova, P. Capilla, J.M. Artigas, M.J. Luque and A. Felipe, ATTD: a new colour vision model based on the physiology of the visual system. The 10th Congress of the International Colour Association (AIC'05) 8-13 May, Granada, Spain, 2005. pg 1007-1010.
[24] J. Gómez-Chova, J.M. Artigas, P. Capilla, A. Felipe and M.J. Luque, Testing the perfomance of ATTD colour vision model. The 10th Congress of the International Colour Association (AIC'05) 8-13 May, Granada, Spain, 2005. pg 1011-1014.
[25] E. Chorro, FM. Martínez-Verdú, D. de Fez, P. Capilla and MJ. Luque, Analysing the metrics of the perceptual space in a new multistage physiological colour vision model. Color Res Appl. *In revision*.

Author Biography

Elísabet Chorro received her BS in Physics (Optics branch) from the University of Valencia at Valencia in 2003 and her MSc Dissertation on Physics from the Department of Physics, Systems Engineering and Signal Theory at the University of Alicante (Alicante, Spain) in 2006. Since 2004 she works with the Color and Vision Group of the University of Alicante. Her work has primarily focused on Industrial Colorimetry, Color Vision and Color Imaging.

Francisco Martínez-Verdú received his BS in Physics (Optics branch) from the University of Valencia at Valencia in 1993 and his PhD in Physics from Technical University of Catalonia at Terrassa (Barcelona, Spain) in 2001. Since 1998 he teaches Vision Sciences (including Color Science and Visual Ergonomics) at School of Optics & Optometry in the University of Alicante (Spain). His work has primarily focused on Industrial Colorimetry, Color Management and Color Imaging. He is a member of AIC, EOS and IS&T.