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CHANGES IN COLOUR PERCEPTION WITH AGEING

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ABSTRACT

Purpose. We assessed chromatic sensitivity along the protan, the deutan, and the tritan line (Cambridge Colour Test, CRS Ltd.), the loci of the unique hues (red, green, yellow, blue) and the achromatic locus (neutral grey) for a very large sample (n=185) of colour-normal observers ranging from 18 to 75 years of age. Visual judgements were obtained under normal viewing conditions using broad-band self-luminous stimuli (CRT) under controlled adaptation conditions. *Results.* Trivector discrimination thresholds increased as a function of age along the protan, the deutan, and the tritan axis (with coefficient of determination of $R^2 > 0.1$), with the largest increase being present along the tritan line, which is consistent with the known age-related changes in the lens. We find less pronounced shifts in unique hue settings. Unique red and unique yellow settings do not change with age. Unique blue shifts towards green and unique green shift towards yellow; however, the coefficient of determination is very small in both cases ($R^2 <0.1$). Similarly, the locus of neutral grey is not affected by age ($R^2 <0.1$). *Conclusion.* We conclude that the chromatic sensitivity deterioriates significantly with age, whereas the appearance of unique hues and neutral grey is much less affected remaining almost constant despite the known changes in the ocular media. Our study provides useful normative data both for sensitivity and appearance changes with ageing.

Keywords: Aging, Unique hue, Chromatic sensitivity, Neutral grey.

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INTRODUCTION

The purpose of this study was to assess how colour perception changes with ageing. Of particular interest was how changes in sensitivity are related to changes in colour appearance. We therefore measured chromatic sensitivity as well as unique hues and the locus of the neutral grey for observers ranging from 18 to 75 years of age. 'Unique hues' were first mentioned by Hering[1] who proposed that any hue can be described in terms of its redness or greenness and its yellowness or blueness. Red and green are opposite hues because they cannot be elicited simultaneously by a single colour stimulus; the same is true for blue and yellow. This observation led Hering to postulate the existence of two opponent channels coding red-green and yellow-blue sensations. Quantitative estimates of these two colour-opponent channels were first obtained by Jameson and Hurvich[2] using a hue cancellation technique. Since the pioneering work by Jameson and Hurvich, several studies have investigated how ageing affects the 'Unique hues'. Low and behold, these studies reveal a remarkable invariance of the unique hues with age[3] which is surprising given that there are substantial changes in the ocular media transmission over the life span; the lens becomes more opaque with increasing age which reduces the light that reaches the retina, in particular at short wavelengths[4]. From the light absorption in the ocular media one expects larger sensitivity losses for S-cone isolating stimuli with increasing age which is consistent with S-cone isolating two-colour increment thresholds[5].

Early studies investigating the effect of age on the appearance of unique hues employed monochromatic lights while the observers were dark-adapted. Shefrin and Werner[6] reported that spectral unique yellow and unique blue stay constant throughout the life span, whereas the locus of unique green shifts slightly towards shorter wavelengths. Few studies investigated colour appearance changes under natural viewing conditions using broadband stimuli. Webster and his colleagues[7-9] used Munsell Chips, as well as printed and self-luminous hue palettes to examine the inter-observer variability of unique-hue judgements. They found little evidence for a correlation between hue settings

and age in their sample and concluded that age is not likely to account for the pattern of colour appearance differences across their groups. Interestingly, the inter-observer variability in the unique hue settings was also not predicted by the chromatic sensitivity along the cone-opponent axes (L-M; S-(L+M)) of the observers[10]. Using a hue scaling technique of spectral lights, Abramov and Gordon[11] concluded that unique hues are rather invariant with age, despite the significant age-related changes in the lens and the retina. Shefrin and Werner [12] showed that the achromatic locus (neutral grey) did not change with age, despite the fact that less short-wavelength light reaches the retina due to age-related lens changes. Knoblauch *et al* [13] and Boon *et al* [14] showed that development of chromatic sensitivity persists into early adulthood.

The main purpose of the current study is to evaluate age-related chromatic sensitivity and colour appearance changes in the *same set of observers*. We are using a much larger sample (n=185) of adult colour-normal observers covering a larger age range (18 to 75 years of age) than previously used. We assessed three visual functions in each of the observers: chromatic sensitivity along the protan, deutan and tritan line, the loci of the four unique hues, and the locus of the achromatic point. The first goal is to provide normative data for these three tasks based on a large sample of colour-normal observers. We were interested in assessing whether the inter- and intra-observer variability is increasing with age and whether there is a differential change in variability across the four unique hues. Secondly, we want to explore whether sensitivity and appearance changes show a similar age dependency

EXPERIMENTAL METHOD

We assessed the performance in three different visual tests: (1) Chromatic sensitivity along the protan, deutan, and tritan line (Trivector test; Cambridge Colour Test); (2) Loci of the four unique hues: red, green, yellow, blue. (3) Locus of the neutral grey.

Equipment. Stimuli were displayed on CRT monitor (21-inch Sony GDM-F520) which was controlled by a DELL PC with a VSG2/5 graphics card (Cambridge Research System, Ltd.). The lookup tables were linearised using the ColourCal calibration device (Cambridge Research System, Ltd.) which interfaces with the graphics card. Calibration was checked with a PR650 tele-spectroradiometer (PhotoResearch). The CRT monitor had a correlated colour temperature of about 9300K with a peak luminance of 120 cd/m^2. The CIE coordinates (x, y, Luminance) of the phosphors at peak output were as follows: red = 0.627, 0.342, 28.12; green = 0.287, 0.608, 80.96; blue = 0.151, 0.074, 14.16, respectively. Since there was some initial monitor drift, the monitor was switched on at least one hour before the start of the experiment. The responses of the observers were collected using a button box (CT6, Cambridge Research System, Ltd.). Stimuli were generated using the CRS MatLab toolbox and MatLab 7.4.

Subjects. 185 (82 males and 103 females) naïve subjects participated in the experiment. Their mean age was 34.03 years (range: 18-75 years). The numbers of participants in different age categories is shown in Table 1. Subjects were paid and informed consent was obtained from all subjects prior to the experiment. The experiments were approved by the Ethics committee of the School of Psychology, University of Liverpool. Subjects who had cataract surgery or any other uncorrected vision problems were excluded from the analyses.

Cambridge Colour Test (CCT). All observers were tested with the Cambridge Colour Test[15]: thresholds along the protan, the deutan and the tritan line were assessed (Trivector thresholds). Only observers that fell within the normal range were used for the unique hue experiments. Normal range was defined as thresholds lower than 100×10^{-4} *u'v'* units for the protan and deutan lines, and lower than 150×10^{-4} *u'v'* units for the tritan line. Observers with thresholds beyond these limits received a small fee and were excluded from further experiments. All data reported in the results section are therefore from a colour-normal sample.

Unique Hue Selection Task. To obtain settings of the unique hues we used a modified hue selection task[16]. Patches of similar colours were arranged along an annulus at constant eccentricity (Figure 1)

and the task of the observer was to select a patch that contains neither yellow nor blue (to obtain unique red and green). Unique yellow (blue) was obtained by asking observers to select a patch that contains neither red nor green. Two different viewing patterns, as shown in Figure 1, were used in the current study. In each of the patterns, ten coloured patches were arranged on an annulus, either in a random order (Figure 1a) or regularly ordered according their blue-yellow (red-green) content (Figure 1b). A subset of observers (n=30) was tested with the random pattern to ensure that no bias is introduced by the regular pattern. We found no difference in the unique hue settings obtained with regular vs. random patterns; we therefore decided to use the regular pattern for the majority of the observers since it facilitates the task for naive observers and speeds up the data collection.

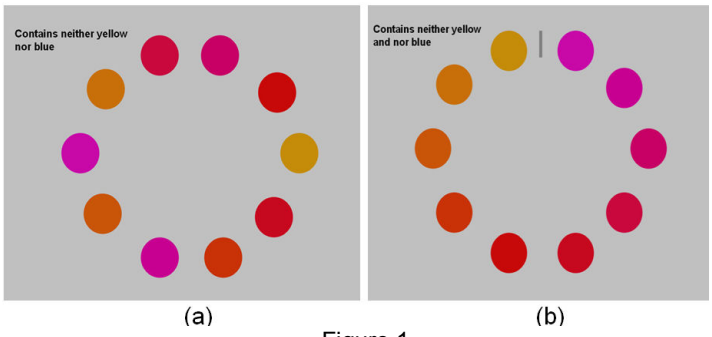


Figure 1

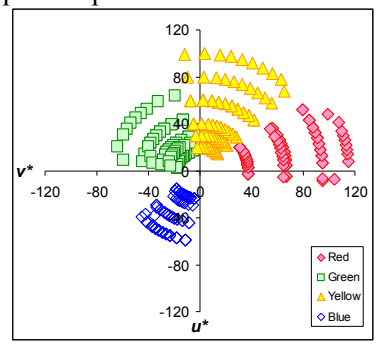


Figure 2

Figure 1 Viewing patterns used in the experiment. (a): random pattern; (b): regular pattern
Figure 2 The 360 colours selected to investigate unique hue settings in the CIELUV space, u^* vs. v^*

The background was always set to a mid-grey with a lightness (L^*) of 50, i.e., having a luminance of 20% of the peak white, *i.e.,* 23.9 cd/m^2. Each patch had a diameter of 2º of visual angle and was presented at an eccentricity of 4º.

Figure 2 shows the test colours in CIELUV [17] colour space (u^* *vs.* v^*). Each unique hue was assessed at different lightness and saturation levels as shown in figure 2. On a particular trial, the ten coloured patches had the same lightness L^* and saturation C_{uv}^* value; the test colours were of similar perceptual differences (i.e. approximately equally spaced in u^*v^* diagram). The particular saturation and lightness levels were chosen to maximise the available gamut. Each unique hue was determined at nine combinations of different saturation and lightness levels. Each of these nine settings was repeated three times to obtain an estimate for the reliability (intra-observer variability). Pilot studies ensured that the chosen hue differences between patches were small enough to determine the intra- and inter-observer variability. In total, 360 test colours (4 unique hues × 9 combinations of different saturation-lightness levels × 10 colour patches per test) were selected. We will report the data in the hue selection task in terms of hue angle in the u^*v^* diagram where hue angle[15] is defined as follows:

$$h_{uv} = \tan^{-1}(v^*/u^*) \quad (1)$$

Neutral Grey settings. The settings for neutral grey were obtained in the same manner as the unique hues; neutral grey was defined as the greyish patch which is neither red nor green and (at the same time) neither yellow nor blue.

RESULTS

Our aim was to investigate how chromatic sensitivity and colour appearance is affected by age and whether the appearance changes are accounted for changes in sensitivity along the cone-isolating directions. We therefore measured sensitivity and appearance changes in the same group of observers. We first report the changes in chromatic sensitivity, and then the changes in unique hues as a function of age.

1. Chromatic sensitivity

The Cambridge colour test (CCT) was used to measure the sensitivity along the protan, deutan and tritan lines. The means obtained in the Trivector Test for each age group are shown in Table 1.

Table 1. Thresholds for different age categories (units: u'v' x 10^{-4})

Age	Below 30	31-40	41-50	51-60	Over 60	All
Number	106	22	21	20	16	185
Protan	50.73	56.35	58.05	63.75	67.00	55.07
Deutan	47.55	51.57	52.95	59.40	67.47	51.66
Tritan	70.06	72.74	75.70	91.60	114.67	77.95

Our CCT results are in excellent agreement with previous studies for the young age (18-30y) group[18] and show a clear loss of sensitivity with increasing age. Previous studies using the CCT have failed to find a significant effect of age in the adult population[19].

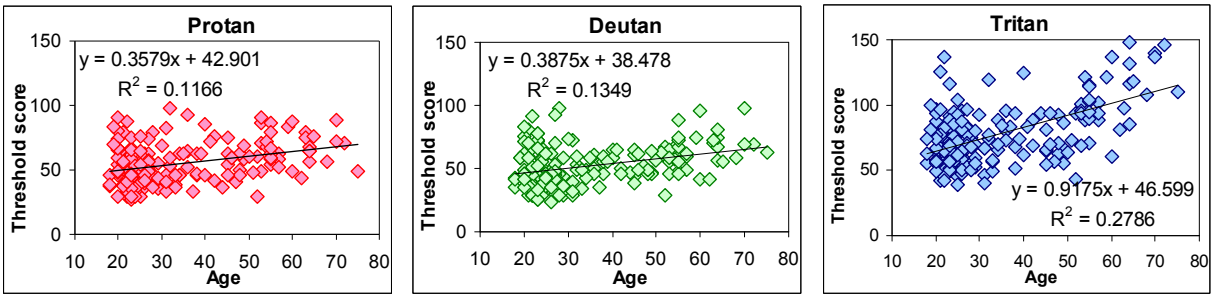


Figure 3 CCT (Trivector test) results plotted as a function of age

Figure 3 shows the Protan, Deutan, and Tritan thresholds for all 185 observers as a function of age. Parameters for the least-squares linear regression equations are shown in Table 2; the null hypothesis of the t-test is that the slope is equal to 0, i.e. thresholds do not depend on age. Although the coefficient of determination (R^2) is not very large, the increase of thresholds on age is highly significant for all three tests (protan, deutan, tritan) due to the large sample size. The R^2 values are 0.11, 0.13 and 0.28 for protan, deutan and tritan thresholds, respectively, and are lower than those reported previously [13, 14]. Knoblauch *et al* [13] obtained R^2 values of about 0.8 when predicting chromatic thresholds as a function of log(age) since their study concentrated on infants. A likely reason for our smaller R^2 is the inclusion of a significant number of older observers in our study; variability in thresholds in the ageing population is caused by numerous optical and retinal factors. Secondly, a non-linear model such as an accelerating non-linear function might provide a better fit. Regardless of the exact age dependency, chromatic sensitivity clearly declines with ageing with almost identical slopes for protan and deutan thresholds; hence any mechanism taking the difference between the L and M cone signals should not be affected by the age-related loss in sensitivity.

Table 2 Parameters of linear regression as a function of age for CCT results

	Protan		Deutan		Tritan	
	Intercept	Slope	Intercept	Slope	Intercept	Slope
Value	42.922	0.357	38.475	0.388	46.061	0.938
Standard Error	2.694	0.073	2.685	0.073	4.105	0.111
t	4.90		5.34		8.45	
p	1.05E-06		1.37E-07		4.44E-15	
R^2	0.1166		0.1349		0.2786	

2. Unique hue settings

Hue angles as a function of age. Figure 4 shows the hue angles for all four unique hues as a function of age for all 185 observers. Parameters for the least-squares linear regression equations are shown in Table 3. For all hues, hue angles are fairly constant across age which is reflected in the slope being close to zero and the very small R^2 (almost 0 for red and yellow; 0.032 for unique green; 0.035 for unique blue): the slope for the regression lines do not differ significantly from 0 for red and yellow (Table 3); there is a small, but statistically significant decrease of hue angle as a function of age for unique green and unique blue.

The lack of age dependency for yellow is consistent with results by Schefrin and Werner[6] who investigated spectral unique hues for 50 subjects ranging in age from 13 to 74 years. They reported a shift of unique green towards shorter wavelength which is inconsistent with our data; furthermore, they failed to find an age dependency for unique blue. Abramov and Gordon[11] reported that none of the three spectral hues (yellow, green, blue) varied as a function of age. The discrepancies between previous studies may in part be due to methodological differences and different sample sizes.

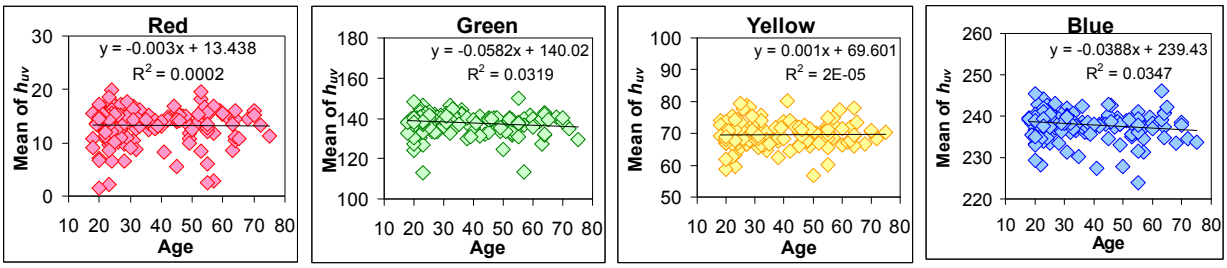


Figure 4 Unique-Hue angles plotted as a function of age

Table 3 Parameters of linear regression as a function of age for all four unique hues

	R		G		Y		B	
	Intercept	**Slope**	**Intercept**	**Slope**	**Intercept**	**Slope**	**Intercept**	**Slope**
Value	13.42	0.00	140.02	-0.06	69.57	0.00	239.39	-0.04
Standard Error	0.63	0.02	0.88	0.02	0.64	0.02	0.56	0.02
t	-0.15		-2.45		0.11		-2.50	
p	0.4405		0.0076		0.4563		0.0066	
R^2	0.0002		0.0319		0.00002		0.0347	

Variability of unique hue settings as a function of age. We assessed the variability between observers and the repeatability within observers as a function of age, in terms of perceptual differences. Since CIELUV space is approximately uniform, Euclidean distances in this space correlate with perceptual distances. The colour difference, ΔE^*_{uv}, is calculated as Equation 2, where $\Delta L^*, \Delta u^*, \Delta v^*$ are the differences between the two colours in the L^*, u^*, v^* dimensions, respectively:

$$\Delta E^*_{uv} = \sqrt{\Delta L^{*2} + \Delta u^{*2} + \Delta v^{*2}} = \sqrt{\Delta L^{*2} + \Delta C^*_{uv}{}^2 + \Delta H_{uv}{}^2}$$

$$\text{with} \quad \Delta H_{uv} = 2\sin(\Delta h_{uv}/2)\sqrt{C^*_{uv,1}C^*_{uv,2}} \quad \textit{and} \quad \Delta C^*_{uv} = C^*_{uv,1} - C^*_{uv,2} \qquad (2)$$

Intra-observer variability. Each observer repeated each unique hue judgement (same saturation and same luminance) three times. For each saturation and luminance level, the colour differences between the individual settings and the average setting were calculated. The intra-observer variability was then defined as the root-mean-square (RMS) error, since the RMS value reflects the average deviation of each individual setting from the mean setting for a particular observer. This intra-observer variability for all observers plotted as a function of age is shown in Figure 5 (a) and parameters for the least-squares linear regression equations are shown in Table 4. We find no statistically significant age-related change in intra-observer variability for the four unique hues studied.

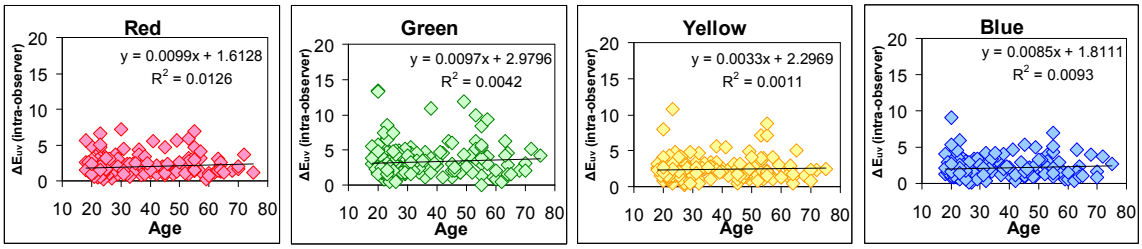


Figure 5 (a) Intra-observer variability in terms of colour difference (ΔE^*_{uv}) plotted as a function of age

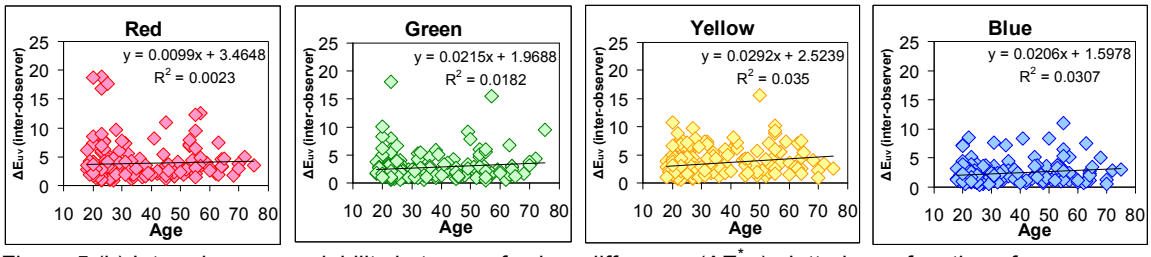


Figure 5 (b) Inter-observer variability in terms of colour difference (ΔE^*_{uv}) plotted as a function of age

Table 4 Parameters of linear regression as a function of age for intra-observer variability

	R		G		Y		B	
	Intercept	**Slope**	**Intercept**	**Slope**	**Intercept**	**Slope**	**Intercept**	**Slope**
Value	1.62	0.01	2.99	0.01	2.31	0.00	1.83	0.01
Standard Error	0.24	0.01	0.41	0.01	0.27	0.01	0.24	0.01
t	1.49		0.86		0.40		1.24	
p	0.068973		0.1955		0.3448		0.1083	
R^2	0.0126		0.0042		0.0011		0.0093	

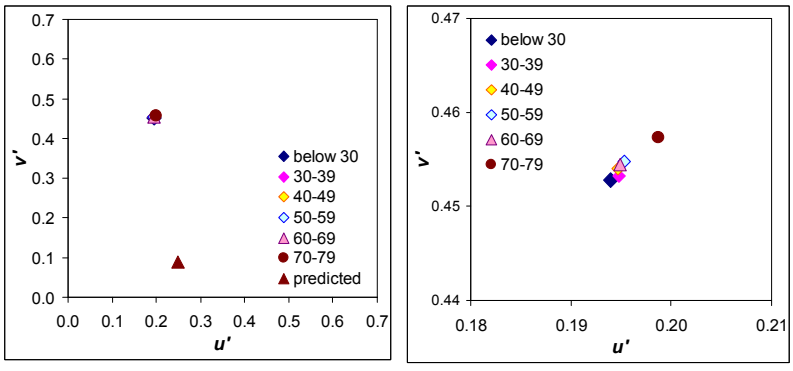
Inter-observer variability. The inter-observer variability reflects how well different observers agree in terms of their hue settings and is defined as the RMS value of colour differences (ΔE^*_{uv}) between the individual observer's setting (mean value of the three repetitions) and the mean value across all observers. Figure 5 (b) shows the inter-observer variability for all observers plotted as a function of age and parameters for the least-squares linear regression equations are shown in Table 5. For unique green, yellow and blue we find a significant increase in inter-observer variability with age; for unique red this age-correlated change did not reach statistical significance. However, the coefficient of determination (R^2) is very small for all unique hues ($R^2 < 0.1$).

Table 5 Parameters of linear regression as a function of age for inter -observer variability

	R		G		Y		B	
	Intercept	**Slope**	**Intercept**	**Slope**	**Intercept**	**Slope**	**Intercept**	**Slope**
Value	3.47	0.01	1.97	0.02	2.56	0.03	1.63	0.02
Standard Error	0.56	0.02	0.43	0.01	0.42	0.01	0.32	0.01
t	0.65		1.85		2.48		2.29	
p	0.2583		0.0330		0.0070		0.0116	
R^2	0.0023		0.0182		0.035		0.0307	

3. Neutral grey

The neutral grey settings for all observers are shown in Figure 6 together with the predictions for the oldest age group (adapted from Werner [3]). Figure 6 (b) is an enlarged version of Figure 6 (a); the shift of the achromatic locus as a function of age is negligible ($R^2 < 0.1$).



(a) (b)

Figure 6 (a) Observer neutral grey settings and the predicted neutral grey for age 70-79; (b) Blown-up plot of observed settings

CONCLUSION

We assessed chromatic sensitivity (CCT Trivector thresholds), unique hue (red, green, yellow, blue) settings, and the locus of the achromatic point for a very large sample (n=185) of colour-normal observers ranging from 18 to 75 years of age. Visual judgements were obtained under normal viewing conditions using broad-band self-luminous stimuli (CRT). Trivector discrimination thresholds increased as a function of age (with an $R^2 > 0.1$), in particular along the tritan line, which is consistent with the 'yellowing' of the ageing lens. We find less pronounced age effects in unique hue settings and neutral grey. Unique red and unique yellow settings do not change with age. Unique blue shifts towards green and unique green shifts towards yellow; however, the coefficient of correlation is very small in both cases ($R^2 < 0.1$). We conclude that the chromatic sensitivity deteriorates significantly with age, whereas the appearance of unique hues and neutral grey is much less affected by age and remains almost constant despite of known changes in the ocular media.

ACKNOWLEDGEMENTS

The equipment was funded by the Wellcome Trust (GR/080205). This work has been supported by TruColour Ltd and the Spanish research project TIN2008-04998; KX and CF were supported by TruColour Ltd.

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