# Investigation of unique hue setting changes with ageing

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Clromatic sensitivity along the protan, deutan, and tritan lines and the loci of the unique hues (red, green, yellow, blue) for a very large sample ($n$ = 185) of colour-normal observers ranging from 18 to 75 years of age are assessed. Visual judgments are obtained under normal viewing conditions using colour patches on self-luminous display under controlled adaptation conditions. Trivector discrimination thresholds show an increase as a function of age along the protan, deutan, and tritan axes, with the largest increase present along the tritan line, less pronounced shifts in unique hue settings are also observed. Based on the chromatic (protan, deutan, tritan) thresholds and using scaled cone signals, we predict the unique hue changes with ageing. A dependency on age for unique red and unique yellow for predicted hue angle is found. We conclude that the chromatic sensitivity deteriorates significantly with age, whereas the appearance of unique hues is much less affected, remaining almost constant despite the known changes in the ocular media.

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This study aimed at assessing how hue perception changes with ageing and at investigating how chromatic sensitivity changes relate to hue perception. Particular interest was on how changes in sensitivity were related to changes in colour appearance. Therefore, we measured chromatic sensitivity as well as unique hues for observers ranging from 18 to 75 years of age. 'Unique hues' were first mentioned by Hering, who proposed that any hue can be described in terms of its redness or greenness and its yellowness or blueness[1]. 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 opposing channels responsible for coding red-green and yellow-blue sensations. Quantitative estimates of these two colour-opponent channels were first obtained by Jameson *et al.* in a pioneering work using a hue cancellation technique[2]. Since then, several studies have investigated how ageing affects the 'unique hues'. These studies reveal a remarkable invariance of the unique hues with age, which is surprising given the substantial changes in ocular media transmission over its life span[3]; the lens becomes more opaque with increasing age, which reduces the light that reaches the retina, particularly 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 *et al.* reported that spectral unique yellow and unique blue stayed constant throughout the life span, whereas the locus of unique green shifted slightly towards shorter wavelengths[6]. Few studies investigated colour appearance changes under natural viewing conditions using broadband stimuli. Webster *et al.* used Munsell Chips, as well as printed and self-luminous hue palettes, to examine the inter-observer variability of unique-hue judgements[7−9]. They found little evidence for a correlation between hue settings and age in their sample, and concluded that age was not likely to account for the pattern of colour appearance differences across their groups. Similarly, they found that distributions of hue loci remained stable across diverse populations. Interestingly, the inter-observer variability in the unique hue settings was 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 *et al.* concluded that unique hues were rather invariant with age, despite significant age-related changed in the lens and the retina[11]. Shefrin *et al.* showed that the achromatic locus (neutral grey) did not change with age, despite the fact that less short-wavelength light reached the retina due to age-related lens changes[12]. Knoblauch *et al.* showed that the development of chromatic sensitivity persisted into early adulthood[13,14]. Note that Knoblauch *et al.* focused on young infants, whereas different age ranges of adults were the concern in our study. Okajima *et al.* compared unique hue settings between six young and elderly subjects by using both a categorical colour naming method and an elemental colour scaling method[15]. Results showed that categorical colour naming between elderly and young subjects was almost the same for most colour chips, although significant differences in the elemental colour scaling between the two age groups were observed.

We focused on the evaluation of age-related chromatic sensitivity and hue appearance changes in the same set of observers because previous studies used different groups of observers to investigate the effect of age on chromatic sensitivity and on hue perception. We used a significantly larger sample ($n$=185) of adult colour-normal observers covering a larger age range (18–75 years of age) than previously used. Three visual functions were assessed in

 

each observer: chromatic sensitivity along the protan, deutan, and tritan lines; the loci of the four unique hues; the locus of the achromatic point. The first goal was 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 variabilities increased with age and whether a differential change in variability across the four unique hues existed. Secondly, we explored whether sensitivity and appearance changes showed a similar age dependency. Finally, we scaled the cone coordinates $(L, M, S)$ with the individual threshold in order to take into account individual observer sensitivity. Subsequently, we estimated hue changes with ageing and compared the observed and predicted hue perceptions as a function of age.

We assessed the performance in two different visual tests: (1) chromatic sensitivity along the protan, deutan, and tritan lines; (2) Loci of the four unique hues: red, green, yellow, and blue.

Stimuli were displayed on a cathode ray tube (CRT) monitor (21-inch Sony GDM-F520, Japan) controlled by a DELL PC with a VSG2/5 graphics card (Cambridge Research System Ltd., England). The lookup tables were linearised using the ColourCal calibration device (Cambridge Research System, Ltd., England) which interfaced with the graphics card. Calibration was checked with a PR650 tele-spectroradiometer (PhotoResearch). The CRT monitor had a correlated colour temperature of about 9300 K 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, and 28.12; green = 0.287, 0.608, and 80.96; blue = 0.151, 0.074, and 14.16, respectively. The monitor was switched on at least 1 h before the start of the experiment because of the initial monitor drift. The responses of the observers were collected using a button box (CT6, Cambridge Research System Ltd., England). Stimuli were generated using the CRS MatLab toolbox and MatLab 7.4.

185 naive subjects (82 males and 103 females) with normal colour vision and who have not undergone a cataract operation participated in the experiment. Mean age was 34.03 years (range: 18–75 years). The number of participants in different age categories is shown in Table 1. 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 underwent cataract surgery or any other uncorrected vision problems were excluded from the analyses.

All observers were tested with the Cambridge Colour Test (CCT)[16]: thresholds along the protan, deutan, and tritans line were assessed (Trivector thresholds). Only observers that were classified within the normal range were used for the unique hue experiments. Normal range was defined as thresholds lower than $100\times10^{-4}$ $u'v'$ units for the protan and deutan lines, and lower than $150\times10^{-4}$ $u'v'$ units for the tritan line. Observers with thresholds beyond these limits were excluded from further experiments.

To obtain settings of the unique hues, we used a modified hue selection task[17]. Patches of similar colours were arranged along an annulus at constant eccentricity (Fig. 1). The task of the observer was to select a patch that contained neither yellow nor blue in order to obtain unique red and green. Unique yellow or blue was obtained by asking observers to select a patch that contained neither red nor green. Two different viewing patterns are used, as shown in Fig. 1. In each pattern, 10 coloured patches were arranged on an annulus, ordered either randomly (Fig. 1(a)) or regularly according to their blue-yellow or red-green content (Fig. 1(b)). A subset of observers ($n$=30) was tested with the random pattern to ensure that no bias was introduced by the regular pattern. Table 2 shows the descriptive statistics results for unique hue selection task with regular versus random patterns. No significant difference was found in the unique hue settings obtained with regular versus random patterns. Note that unique red, unique gerrn, unique yellow and unique blue are refenred as UR UG, UY, and UB, respectively. Consequently, we decided to use the regular pattern for the majority of observers because it facilitated the task for naive observers and speeded up data collection.

**Table 1. Thresholds for Different Age Categories (Units: $u'v'\times10^{-4}$)**

| Age (year) | 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 |

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

Figure 2 shows the test colours in CIELUV[18] colour space ($u^*$ versus $v^*$). Each unique hue was assessed at different lightness and saturation levels (Fig. 2). On a particular trial, the 10 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

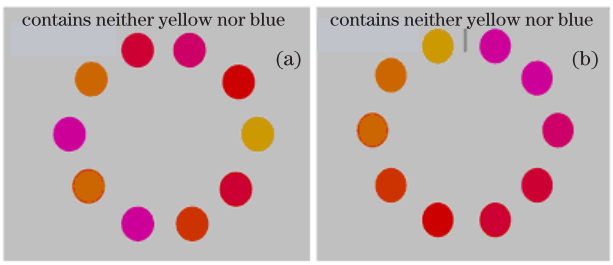


Fig. 1. Viewing patterns used in the experiment. (a) Random pattern; (b) regular pattern.

**Table 2. Descriptive Statistics for Unique Hue Selection Task Results with Regular Versus Random Patterns**

| | Pattern | UR | UG | UY | UB |
|---|---|---|---|---|---|
| Mean Hue Angle | Regular | 13.49 | 137.84 | 69.41 | 238.31 |
| (°) | Random | 12.80 | 137.16 | 70.54 | 238.52 |
| Standard | Regular | 2.24 | 3.84 | 2.77 | 1.935 |
| Deviation (SD) | Random | 5.38 | 4.38 | 2.89 | 3.60 |

differences between patches were small enough to determine the intra- and inter-observer variabilities. A total of 360 test colours (4 unique hues × 9 combinations of different saturation-lightness levels × 10 colour patches per test) were selected. We reported the data in the hue selection task in terms of hue angle in the $u^*v^*$ diagram where hue angle $h_{uv}$ is defined as[15]

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

Our aim was to investigate how chromatic sensitivity and colour appearance were affected by age, and whether the appearance changes could be accounted for by changes in sensitivity along the cone-isolating directions. Thus, sensitivity and appearance changes in the same group of observers were measured. However, the use of the same group of observers which can be followed up over the years is not easy to achieve. Thus, we implicitly assumed that mean results within each age-group was representative.

We first reported the changes in chromatic sensitivity, followed by the changes in unique hues as a function of age. Observed hue perception changes were compared with the predicted hue changes based on the age-related changes in chromatic sensitivity.

The 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.

The CCT results are in excellent agreement with previous studies for the young age group (18–30 years)[19] 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[20].

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 3. The null hypothesis of the $t$-test is that the slope is equal to 0, i.e., thresholds are not dependent on age. Although the coefficient of determination ($R^2$) is not relatively small, the increase of thresholds on age is highly significant for all three tests (protan, deutan, and tritan) due to the large sample size. The $R^2$ values are 0.12, 0.14, and 0.28 for protan, deutan, and tritan thresholds, respectively. These are lower than the values reported previously[13,14]. Knoblauch *et al.* obtained $R^2$ values of about 0.8 when predicting chromatic thresholds as a function of log(age), because their study concentrated on infants[13]. A likely reason for the smaller $R^2$ we obtain 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 nonlinear model such as an accelerating nonlinear function might provide a better fit. The contrast thresholds along the tritan line ($S$-cone isolating stimulis) are strongly related to age. This is consistent with the 'yellowing' of the lens. Regardless of the exact age dependency, chromatic sensitivity clearly declines with ageing with almost identical slopes for protan and deutan thresholds. Hence, any mechanism exhibiting the difference between the $L$- and $M$-cone signals should not be affected by the age-related loss in sensitivity.

The hue angle for each unique hue stimulus assessed by each observer is predicted in CIELUV colour space. Figure 4 shows the hue angles for all four unique hues as a function of age for the 185 observers. Parameters for the least-squares linear regression equations are shown in Table 4. For all hues, hue angles are fairly constant across age, which is reflected in the slope being close to

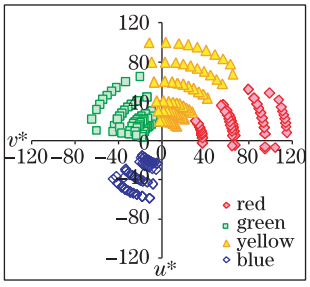


Fig. 2. 360 colours selected in the investigation of unique hue settings in the CIELUV space, $u^*$ vs. $v^*$.

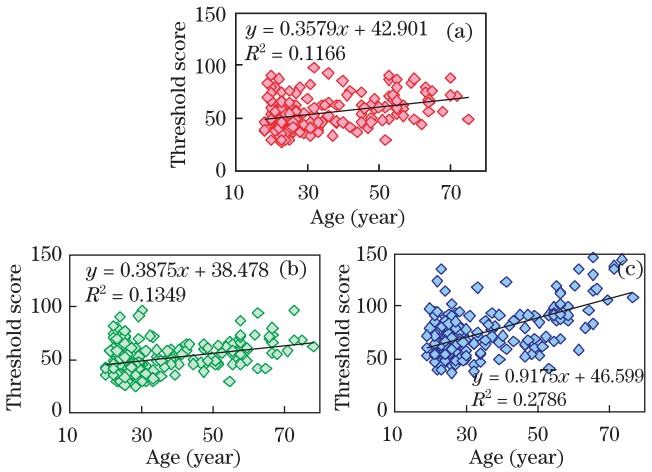


Fig. 3. CCT (Trivector test) results plotted as a function of age. (a) Protan; (b) deatan; (c) tritan.

**Table 3. Parameters of Linear Regression as Function of Age for CCT Results**

| | | Value | Standard Error | $t$ | $p$ | $R^2$ |
|---|---|---|---|---|---|---|
| Protan | Intercept | 42.92 | 2.69 | 4.90 | $1.05\times10^{-6}$ | 0.12 |
| | Slope | 0.36 | 0.07 | | | |
| Deutan | Intercept | 38.48 | 2.69 | 5.34 | $1.37\times10^{-7}$ | 0.14 |
| | Slope | 0.39 | 0.07 | | | |
| Tritan | Intercept | 46.06 | 4.11 | 8.45 | $4.44\times10^{-15}$ | 0.28 |
| | Slope | 0.94 | 0.11 | | | |

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 4). However, a small but statistically significant decrease of hue angle as a function of age for unique green and unique blue was observed.

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

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, $\Delta E^*_{uv}$, is calculated using

$$\Delta E^*_{uv} = \sqrt{\Delta L^{*2} + \Delta^{*2}_u + \Delta v} = \sqrt{\Delta L^{*2} + \Delta C^{*\,2}_{uv}},$$
$$\text{with } \Delta H_{uv} = 2\sin(\Delta h_{uv}/2)\sqrt{C^*_{uv,1}C^*_{uv,2}},$$
$$\text{and } \Delta C^*_{uv} = C^*_{uv,1} - C^*_{uv,2}, \quad (2)$$

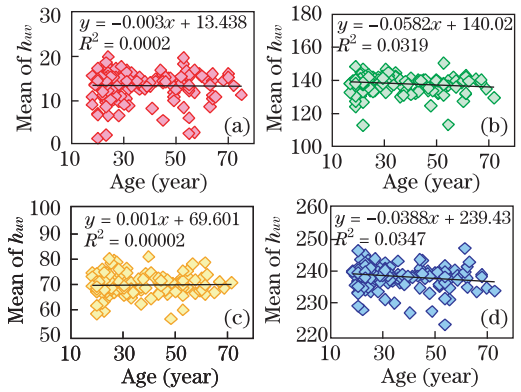


Fig. 4. Unique-hue angles plotted as a function of age. (a) Red; (b) green; (c) yellow; (d) blue.

**Table 4. Parameters of Linear Regression as Function of Age for All Four Unique Hues**

| | | Value | Standard Error | $t$ | $p$ | $R^2$ |
|---|---|---|---|---|---|---|
| UR | Intercept | 13.42 | 0.63 | –0.15 | 0.44 | 0.0002 |
| | Slope | 0.00 | 0.02 | | | |
| UY | Intercept | 140.02 | 0.88 | –2.45 | 0.01 | 0.032 |
| | Slope | –0.06 | 0.02 | | | |
| UG | Intercept | 69.57 | 0.64 | 0.11 | 0.46 | 0.00002 |
| | Slope | 0.00 | 0.02 | | | |
| UB | Intercept | 239.39 | 0.56 | –2.50 | 0.01 | 0.0347 |
| | Slope | –0.04 | 0.02 | | | |

where $\Delta L^*$, $\Delta u^*$, and $\Delta v^*$ are the differences between the two colours in the $L^*$, $u^*$, and $v^*$ dimensions, respectively.

Each observer repeated each unique hue judgement (same saturation and same luminance) three times. For each saturation and luminance level, the colour differences between individual settings and average setting were calculated. Intra-observer variability was then defined as the root-mean-square (RMS) error, because the RMS value reflected 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 Fig. 5. Parameters for the least-squares linear regression equations are shown in Table 5. No statistically significant age-related change in intra-observer variability for the four unique hues studied was found.

The inter-observer variability reflects how well different observers agree in terms of their hue settings. It is defined as the RMS value of colour differences ($\Delta E^*_{uv}$) between the individual observer's setting (mean value of the three repetitions) and the mean value across all observers. Figure 6 shows the inter-observer variabilities for all observers plotted as a function of age. Parameters for the least-squares linear regression equations are shown in Table 6. For unique green, yellow, and blue, we found a significant increase in inter-observer variability

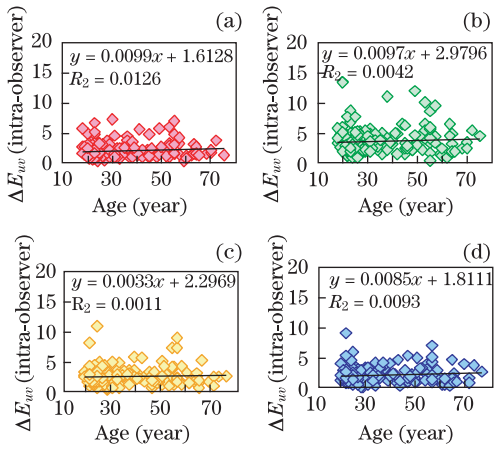


Fig. 5. Intra-observer variability in terms of colour difference ($\Delta E^*_{uv}$) plotted as a function of age. (a) Red; (b) green; (c) yellow; (d) blue.

**Table 5. Parameters of Linear Regression as Function of Age for Intra-observer Variability**

| | | Value | Standard Error | $t$ | $p$ | $R^2$ |
|---|---|---|---|---|---|---|
| UR | Intercept | 1.62 | 0.24 | 1.49 | 0.069 | 0.0126 |
| | Slope | 0.01 | 0.01 | | | |
| UG | Intercept | 2.99 | 0.41 | 0.86 | 0.12 | 0.0042 |
| | Slope | 0.01 | 0.01 | | | |
| UY | Intercept | 2.31 | 0.27 | 0.40 | 0.35 | 0.0011 |
| | Slope | 0.00 | 0.01 | | | |
| UB | Intercept | 1.83 | 0.24 | 1.24 | 0.11 | 0.0093 |
| | Slope | 0.01 | 0.01 | | | |

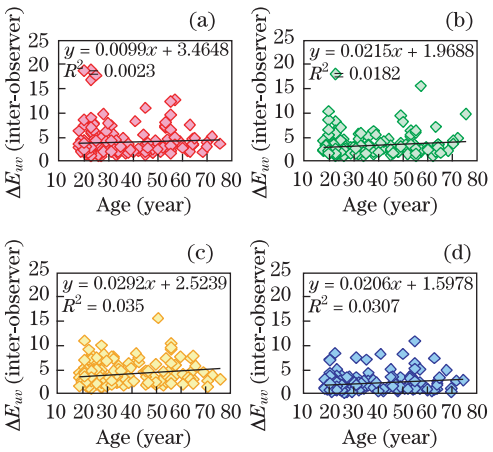


Fig. 6. Intra-observer variability in terms of colour difference ($\Delta E^*_{\mathrm{uv}}$) plotted as a function of age. (a) Red; (b) green; (c) yellow; (d) blue.

**Table 6. Parameters of Linear Regression as Function of Age for Inter-observer Variability**

| | | Value | Standard Error | $t$ | $p$ | $R^2$ |
|---|---|---|---|---|---|---|
| UR | Intercept | 3.47 | 0.56 | 0.65 | 0.26 | 0.0023 |
| | Slope | 0.01 | 0.02 | | | |
| UG | Intercept | 1.97 | 0.43 | 1.85 | 0.03 | 0.0182 |
| | Slope | 0.02 | 0.01 | | | |
| UY | Intercept | 2.56 | 0.42 | 2.48 | 0.01 | 0.035 |
| | Slope | 0.03 | 0.01 | | | |
| UB | Intercept | 1.63 | 0.32 | 2.29 | 0.01 | 0.0307 |
| | Slope | 0.02 | 0.01 | | | |

with age; for unique red, this age-correlated change did not achieve statistical significance. However, the coefficient of determination is very small for all unique hues ($R^2 < 0.1$). Thus, the observation that the appearance of unique hues is less affected is in agreement with previous studies.

In conclusion, through the tests and analysis, we conclude that chromatic sensitivity deteriorates significantly with age, whereas the appearance of unique hues and neutral grey is significantly less affected by age and remains almost constant despite known changes in the ocular media. We also find that the predicted hue angles derived based on the individual observer's sensitivity are age-dependent for unique red and unique yellow, whereas the observed hue angles are not dependent on age. This excludes the possibility that for hue invariance with age, the decline in sensitivity in the $L$, $M$, and $S$ cones is parallel as a function of age. This likewise suggests that human observers might change the individual cone inputs when the effective cone signal based on the neural loss or changes in the lens deteriorates. Our study provides useful normative data both for sensitivity and colour appearance changes with ageing, as well as gives further evidence as basis for further investigation of how the human visual system receives information on the cone inputs and how the system adjusts receptor signals to achieve hue constancy. Based on the accumulated experimental data, further studies have also been conducted to address unique hue in colour appearance reproduction and colour-opponent mechanisms based on age-related chromatic sensitivity changes[21,22].

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