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The Age Effect on Observer Colour Matching and Individual Colour Matching Functions

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Abstract

The visual changes caused by aging have an important effect on human vision. In this study, a series of color matching experiments were conducted to explore the differences in color matching results between observers of different age groups. The experiments were conducted using a visual trichromator, which could be illuminated by 18 LEDs with different peak wavelengths as light sources that formed 11 different triplets of RGB primaries. The matched and reference fields observed by the observers in the experiment were equally sized semicircular fields that together formed a circular field. A fixed triplet of RGB primaries produced the white reference field on the right side. It was matched on the left-side by adjusting the primary intensities of each of the 11 triplets of RGB primaries. The white reference stimulus was fixed at $120\ cd/m^2$ *luminance level. One hundred Chinese observers with normal colour vision were divided by decades into 7 groups from 10 to 80 years old. The matches were analysed to estimate their cone spectral sensitivities and photopigment, macular and lens optical densities. The experimental results show relatively little variability with age, except as expected increases in lens density with age, and older observers showed more inter-observer variability. The analysis suggests that some of the mean colour matching parameters assumed by the CIE, such as the macular pigment optical density, do not apply for these observers.*

Introduction

The ageing human visual system undergoes changes in physiological function that can result in poorer visual performance [1]. Colour discrimination [2-4] and cone sensitivities in general and S-cone sensitivities in particular [5-9] all decline with age. Moreover, the ageing lens become much yellower as it absorbs more and more short-wavelength light [10]. Despite these changes, we maintain a degree of colour constancy over life because of mechanisms that compensate for differential sensitivity losses, so we can be largely unaware of these changes [4, 9]. Here, we measure colour matches as a function of age, which depend on the cone spectral sensitivities, and photopigment, macular and lens optical densities. Since the matches depend on the cone spectral sensitivities, they will be relatively unaffected by overall cone sensitivity losses, but the other factors may play a role. The commonly used standard colorimetric observers for colour matches are the CIE 1931 and CIE 1964 standard colorimetric observers, namely the 2° and 10° observers [11]. The CIE 1931 standard colorimetric observer is based on the cumulative data of Guild (1931) [12] and Wright (1929) [13, 14], while the CIE 1964 standard colorimetric observer is based on the experimental studies of Stiles and Burch (1959) [15] and Speranskaya (1959) [16]. However, rapid technological advancements and underlying errors in the 1931 functions have rendered these two observers less able to meet the demands of new applications, and using the 1931 2° observer can lead to errors in colour reproduction [17, 18].

In 1991, the International Commission on Illumination (CIE) established the Technical Committee TC1-36 with the aim of "establishing a fundamental chromaticity diagram corresponding to the axes of physiological significance." Eventually, this committee agreed on the CIE 2006 2° and 10° colour matching functions and on a model for estimating how they change between 1° and 10° based on changes in the optical densities of the cone photopigments, and macular and lens pigments [19-21]. This became known as the physiological observer model (CIEPO06) [19], which is largely based on the research findings and proposals of Stockman and Sharpe [22]. Starting from the 10° colour matching functions of 47 Stiles-Burch observers [23], this model defines the fundamental observers for 2° and 10° and provides a convenient framework for calculating the average cone spectral sensitivities for any visual field size between 1° and 10° and for ages ranging from 20 to 80 years old.

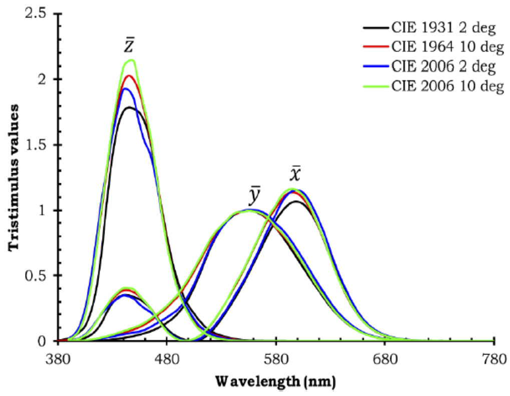

Figure 1. *Illustration of the four CIE CMFs in XYZ form.*

In 2015, Asano *et al.* [24] proposed an individual colorimetric observer model based on CIEP006 using Monte Carlo simulation and performed cluster analysis by modifying k-medoids method [25]. This model can simulate CMFs that represent a population for a given age and a specific field size.

Experimental

Human colour vision can be assessed by measuring colour matches. Two main measurements have been used, namely the maximum saturation method and Maxwell's method. In this study, we used Maxwell's method. Maxwell's method was adopted by Maxwell [26] in 1860 to obtain the first careful, quantitative measurements of trichromatic colour matching and trichromacy. In his method, which is illustrated in Fig. 2, the matched fields always appear white, so that at the match point the eye is always in the same state of adaptation whatever the test wavelength (in contrast to the maximum saturation method in which match chromaticity varies with wavelength). In the experiment, the observer is presented with a white standard half-field, and asked to match it by adjusting the three primary lights in the other half-field. One of the primary lights is then replaced by a test light and a match to the white is repeated.

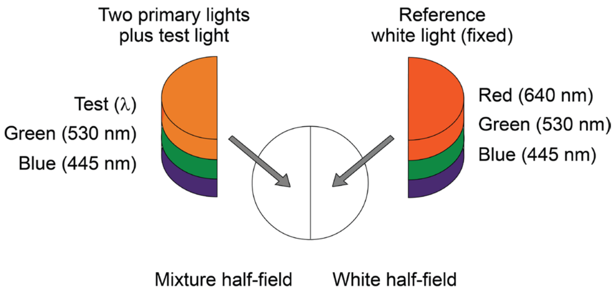

Figure 2. *The Maxwell's colour matching method.*

In this study, a multi-primary visual trichromator named LEDMax was used to perform the colour matching experiment. It consisted of two LED cube, each containing 18 LEDs with different peak wavelengths as light sources. We used 13 of the LEDs in various combinations to form 11 different triplets of RGB primaries as listed in Table 1. The matched and reference fields seen by the observers in the experiment were equally sized semicircular fields that abutted to form a circular field. A fixed set of RGB primaries was used to produce the white reference field on the right side, while the left-side the mixture half-field was made up of each of the 11 sets of RGB primaries. The reference field was fixed at 120 cd/m². The experiment setup is showed in Fig. 3. The fields subtended either a 2 or a 10° field of view (FOV).

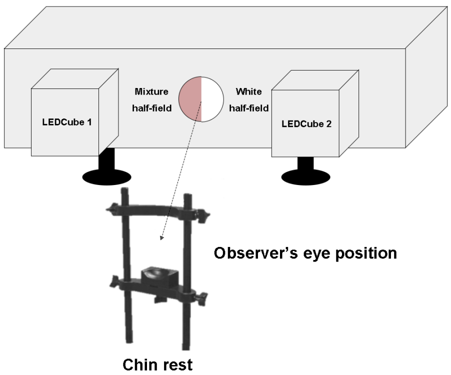

Figure 3. *Colour matching experiment setup.*

In LEDMax, each cube contains 18 different LEDs with peak wavelengths ranging from 400 to 700 nm of which 13 were used in this experiment, the detailed information of these LEDs are listed int Table 1. Based on their relative spectral positions, we can categorize them into red (R), green (G) and blue (B) primaries. We combined them in different ways to produce the 11 RGB primary sets listed in Table 2.

Table 1. The system performance.

Center Wavelength (nm)	FWHM (nm)	Shift (nm)	Peak Luminance (cd/m²)
405	13	1	2.34
415	16	1	4.53
430	17	1	11.22
445	16	3	16.96
460	19	4	27.87
475	30	8	58.91
505	31	5	125.50
530	35	7	160.50
545	39	10	326.90
560	37	1	113.40
575	13	2	13.58
595	14	4	128.70
605	15	3	117.00
640	20	5	63.77
660	16	2	56.40
675	22	3	23.01
705	20	5	1.91
Multi-peak 4700K	/	/	245.60

Table 2. The 11 different primary sets for Mixture half-field.

Primary set	R (nm)	G (nm)	B (nm)
1	640	530	430
2	640	530	445
3	640	530	460
4	640	530	475
5	640	505	445
6	640	545	445
7	640	560	445
8	595	530	445
9	605	530	445
10	660	530	445
11	675	530	445

After spectral calibration, we can transform the primaries into other colour spaces, such as LMS, XYZ, and Lab spaces. Adjustments of the primaries by the observer, using rotary controls, can then be made directly by adjusting the intensities of the primaries themselves, or indirectly by jointly adjusting the primaries to move the match in particular directions in a particular colour space. We found that observers preferred to move the match in L, a and b directions in Lab space and the resulting matches yielded smaller colour matching errors and higher observer consistency than directly controlling RGB. Hence, the indirect colour adjustment method using Lab manipulation was employed in the main experiment. And the reference was set to a white of 7500K in 120cd/m^2, considering the effect of the starting point on the matching accuracy [27], we set the starting point to a darker gray color.

In total, 100 Chinese observers with normal vision participated in this study. Their ages ranged from 8 to 80 years old. They were divided into seven groups by decade as listed in Table 3.

Table 3. Observer numbers in each age group.

Group	Age range	Male	Female	Count
1	8-14	3	7	10
2	20-29	14	16	30
3	30-39	9	6	15
4	40-49	5	10	15
5	50-59	5	5	10
6	60-69	6	4	10
7	70-79	5	5	10
Total	8-80	47	53	100

Psychophysical procedure

Prior to the start of the experiment, the observers underwent Ishihara testing to ensure they had normal colour vision. The entire experiment was conducted in a darkened environment to which the observers adapted for 2 minutes before the start of the experiment. All observers underwent a 30-minute training phase before starting the main experiment. During training, they familiarized themselves with the experimental procedures and practiced making accurate colour matching results. In the main experiments, then observers first made colour matches for a FOV of 10°, until 15 random-order matches were completed (11 matches for each primary set and 4 repeats). After a brief rest and re-adaptation, the observer then completed 15 further random-order sets of colour matches for a 2° FOV (11 matches for each primary set and 4 repeats). The four repeats, which were made for primary sets 2, 3, 6, 10, allowed us to estimate intra-observer variability. In total, each observer had to perform 30 colour matches, which took on average about 60 minutes. Adding adaptation and training, the total duration of the experiment was approximately 90 minutes.

Results

The spectral power distributions (SPDs) of all the triplets of primaries that the observers matched to the white reference standard were measured at the completion of the experiment with a Konica-Minolta CS2000 tele-spectroradiometer (named TSR below) placed at the observer's eye position. We used these SPDs to calculate the spectral shifts of the cone spectral sensitivities, and the photopigment, lens and macular optical densities, which are described below and tabulated in Table 3. We also transformed the SPDs to XYZ tristimulus values using the CIE 2006 2° and 10° standard observers and converted the matches in XYZ to points in the CIE1976 u'v' colour space. For each age group, we fitted 95% confidence ellipses to the inter-observer matches as shown in Figures 4 and 5.

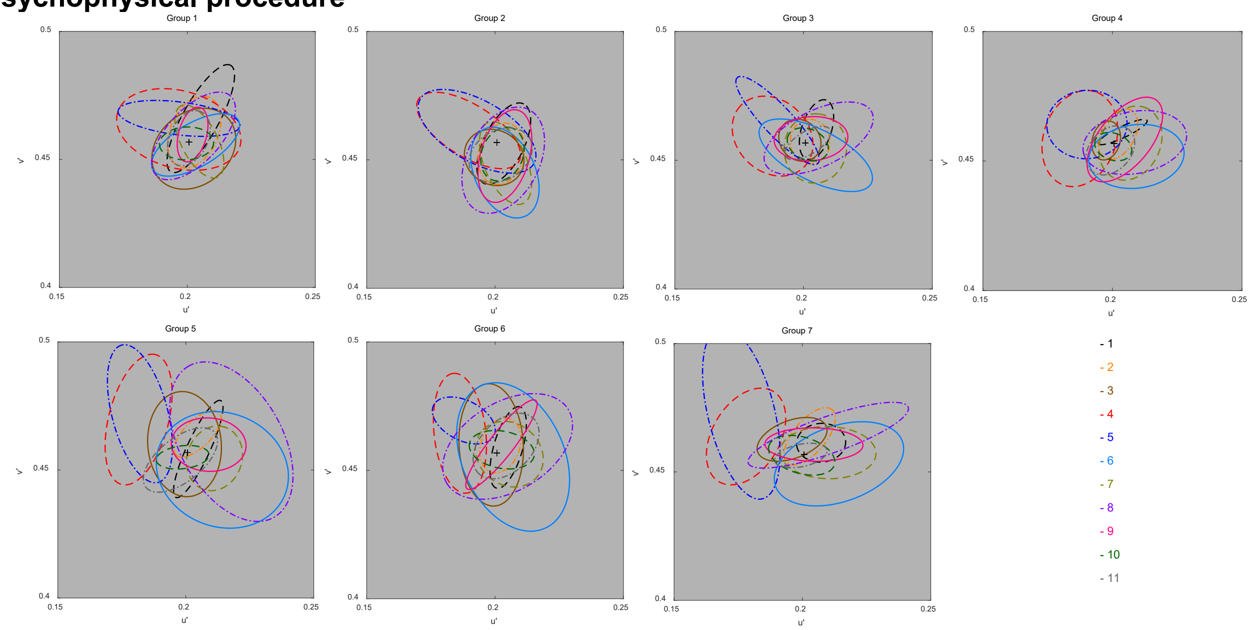

Figure 4. *The distribution of the 95% confidence ellipses fitted to the 2° colour matching data of observers in the CIE 1976 u'v' colour space.*

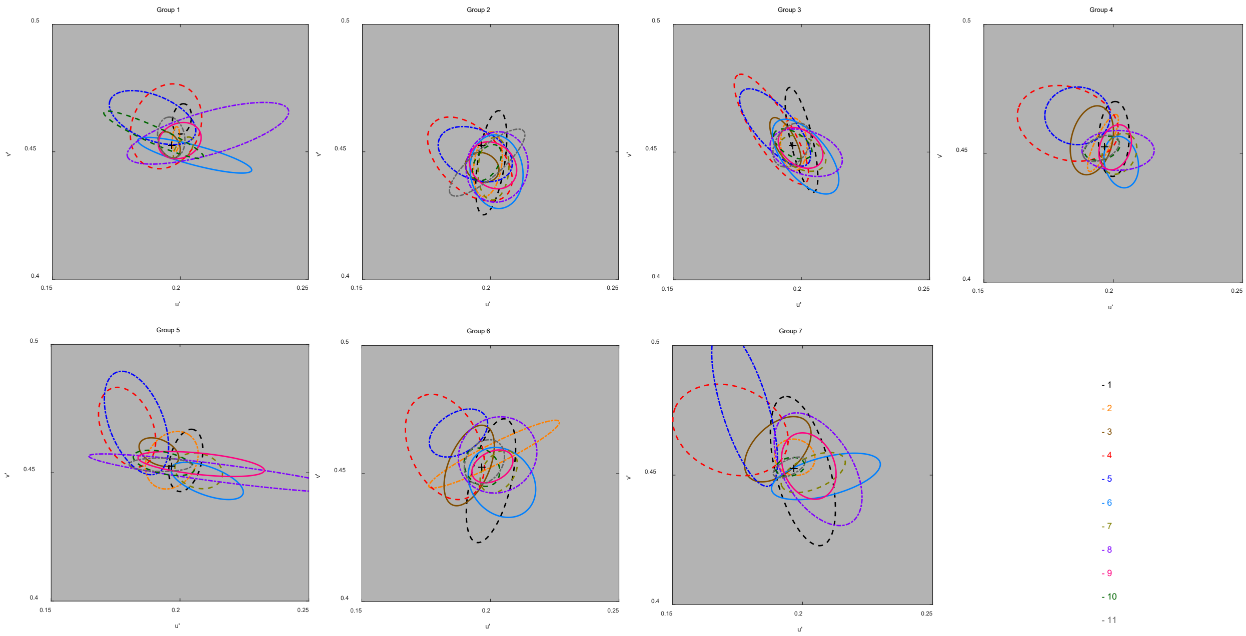

Figure 5. *The distribution of the 95% confidence ellipses fitted to the 10° colour matching data of observers in CIE 1976 u'v' colour space.*

From the fitted ellipses, it can be seen that older observers tend to produce larger ellipses, which means that they have larger inter-observer variability, and their ellipses are more dispersed from the expected white point, suggesting larger matching differences from the CIE standard observers. Young observers also show larger ellipses but closer to the expected matches. We can also calculate the colour matching error, intra- and inter-observer variation to see the effect of age on colour matching. The intra-observer values are calculated from the repeated matches. The mean ΔE_{00} values [28] are plotted in Figure 6.

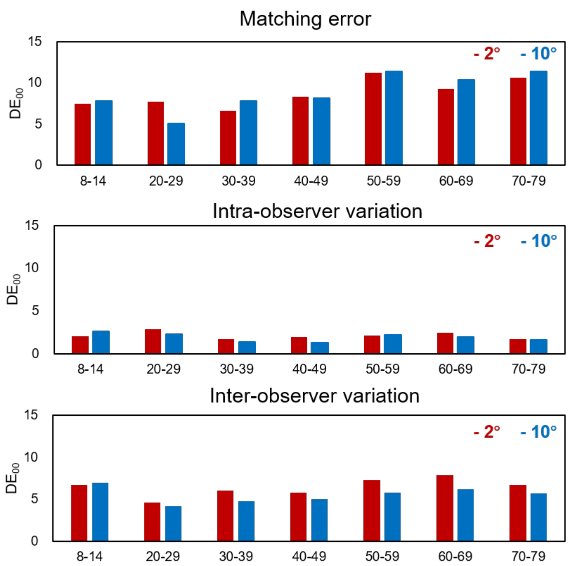

Figure 6. *The matching error, Intra- and Inter- observer variation given by observers in ΔE_{00} units in 2°and 10° experiments.*

The ΔE_{00} values show that the matching errors and inter-observer variations increase with age but the intra-observer variations remain fairly constant, which indicates good repeatability. Meanwhile, the kids (8-14) are giving results that are a little different from the trend. This may be due to two factors: 1. Children are in the developmental stage, and their vision is easily affected by various factors, and at such a stage, the differences between them become even greater. 2. During the actual experiments, their determination of whether the colors match or not differs to some extent from that of adults, and they tend to be much more active and have relatively less patience.

As noted above, the colour matches measured as SPDs were used to derive individual estimates of the cone spectral sensitivities (or fundamental CMFs) based on a computational method of Stockman and Rider [29], which is an extension of the CIEPO06 model. The strategy here was first to derive mathematical functions for the L-, M- and S- cone absorbance spectra and for the standard lens and macular optical density spectra. These were then optimized in spectral position and optical density using a fitting procedure to predict the SPDs of the matches made at 2 and 10°. Seven parameters were optimized: the three optical densities of the L-, M- and S-cones, l_{od}, m_{od} and s_{od}, the lens and macular densities, k_{lens} and k_{mac}, and the spectral shifts of the L and M cones. We fitted this model to each observer's matches, minimising the squared difference in the estimated L, M and S-cone excitations between the reference white spectrum and the 11 matched spectra. Figures 7 and 8 showed the distribution of 7 vision parameters against age, in which the black lines represent the CIE 2006 standard and the red points indicate the fitted parameters for each individual. In addition, the red line shows the mean parameter values and the blue line shows the regression line fitted to them. The correlation coefficient (R^2) is also given in each panel.

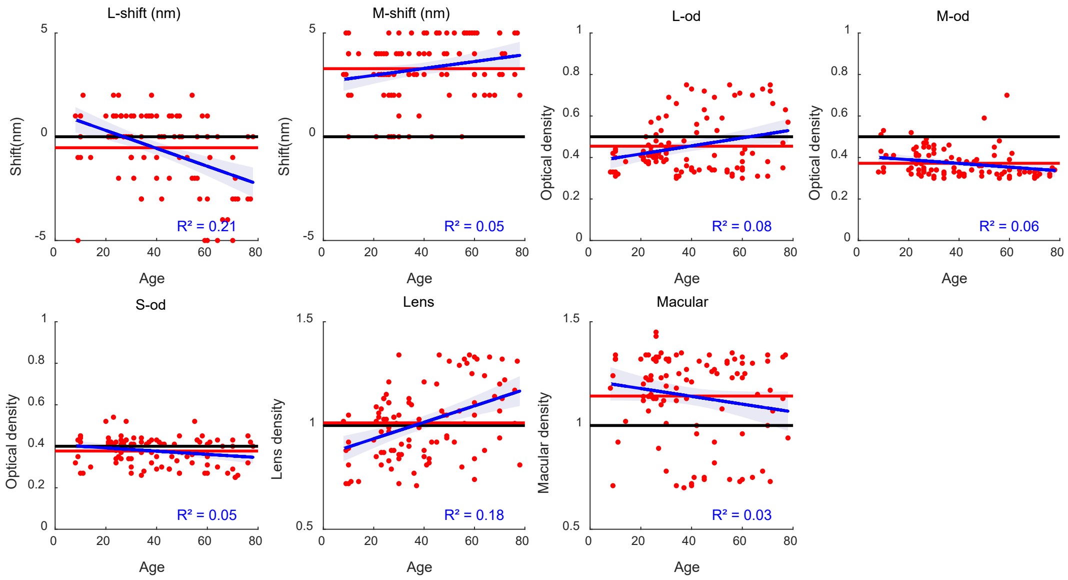

Figure 7. *The distribution of 7 vision parameters against age in the 2° experiment.*

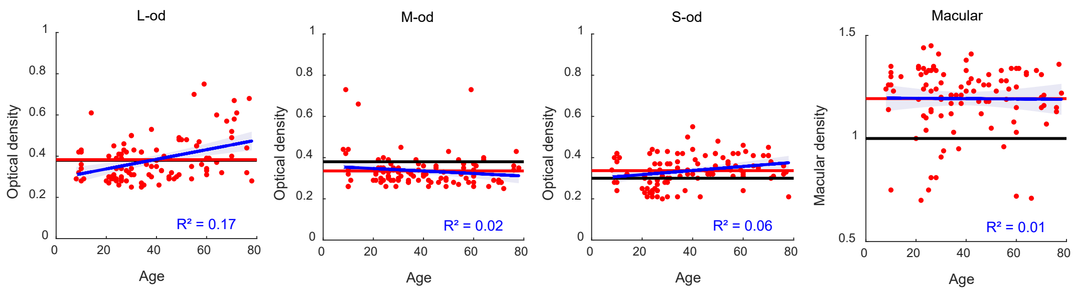

Figure 8. *The distribution of 4 vision parameters against age in the 10° experiment (L-shift, M- shift, and Lens same with 2°).*

The mean parameters for each group are also given in Tables 4 and 5. It was assumed that the L- and M-cone shifts and the lens pigment optical densities for each observer were the same at 2 and 10°.

Table 4. The 2° average vision parameters for each age group.

2°	L-shift	M-shift	L-od	M-od	S-od	Lens	Mac
8-14	-1	3	0.34	0.40	0.37	0.85	1.17
20-29	0	3	0.43	0.39	0.42	1.00	1.25
30-39	0	3	0.45	0.37	0.37	0.95	1.16
40-49	-1	4	0.48	0.34	0.36	0.99	1.02
50-69	-1	4	0.49	0.42	0.40	1.16	1.19
60-69	-2	3	0.44	0.34	0.35	1.10	1.12
70-79	-2	4	0.53	0.32	0.35	1.12	1.14
Mean	-1	3	0.45	0.37	0.37	1.02	1.15

Table 5 The 10° average vision parameters for each age group.

10°	L-shift	M-shift	L-od	M-od	S-od	Lens	Mac
8-14	-1	3	0.37	0.42	0.36	0.85	1.27
20-29	0	3	0.33	0.32	0.29	1.00	1.18
30-39	0	3	0.37	0.33	0.38	0.95	1.16
40-49	-1	4	0.35	0.28	0.39	0.99	1.26
50-69	-1	4	0.48	0.35	0.42	1.16	1.20
60-69	-2	3	0.40	0.29	0.40	1.10	1.15
70-79	-2	4	0.50	0.30	0.40	1.12	1.19
Mean	-1	3	0.40	0.33	0.38	1.02	1.20

In this colour matching function model, the standard values of the vision parameters L- and M- shift are 0 for normal observers, while the standard values of the Lens and Macular are 1. A density of 1 corresponds to a density of 1.76 for the lens at 400 nm and to 0.350 and 0.095 at 460 nm for macular at for 2° and 10°, respectively.

For the other three L-, M-, and S-od, the standard values are [0.50 0.50 0.40] and [0.38 0.38 0.3] for 2° and 10°.

Based on the regression lines and correlation lines shown in Figures 7 and 8, most parameters have a weak or no correlation with age. As expected the lens optical density has a weak positive correlation [10]. The L-shift has a weak negative correlation with age, and thus moved to slightly shorter wavelengths with age, but the reason for this is unclear and may be an artefact. In Tables 3 and 4, the mean positions of the L- and M-cone peaks deviate slightly from the standard values. In addition, the Chinese observers showed a higher level of macular density compared to the CIE 2006 standard observers, which might be differences between ethnic groups or caused by dietary food intake [30]. These findings highlight the importance of considering individual variations in the visual system and age-related changes when studying colour perception.

Conclusion

Age is an important factor that influences human visual perception. In this study, a series of colour matching experiments were performed on observers of different age groups. The observers aged 8 to 80 were divided into seven groups, and their matching data was used to analyze various differences among them. The results showed older observers have greater inter-observer variations and more dispersed centers of ellipse points, while intra-observer variations remain fairly constant, which indicates good repeatability.

Based on Stockman and Rider's method, seven parameters were used to represent the visual identity: the three optical densities of the L-, M- and S-cones, l_{od}, m_{od} and s_{od}, the lens and macular densities, k_{lens} and k_{mac}, and the spectral shifts of the L and M cones. It was found that the positions of the L- and M-cone peak sensitivities deviated slightly from the standard values and in addition these Chinese observers exhibit a higher level of macular density compared to CIE 2006 standard observers, which might be differences between ethnic groups or caused by dietary food intake. Our future work will be focus on individual CMF models and those people with abnormal vision, also to verify other influences on visual properties.

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