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Individual color matches and cone spectral sensitivities in 100 observers of varying age

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Abstract: Previously we reported color matches measured in young adults using a newly developed multi-wavelength LED-based visual trichromator with which we estimated their individual L-, M- and S-cone spectral sensitivities. Here, we extend those measurements to include 70 additional observers aged between 8 to 80 years. As in our previous work, a series of color matching measurements were made to a reference white. Since the spectral power distributions (SPDs) of the matches should produce identical L-, M- and S-cone excitations, we can use them to estimate individual cone spectral sensitivities by fitting an extended version of the CIE physiological observer model (CIEPO06) in which the lens and macular pigment densities, the photopigment optical densities and the L- and M-cone spectral positions can be varied. Overall, the fits were found to be broadly consistent with the CIEPO06 mean standard, but with small spectral shifts of the M- and L-cone photopigments and a denser macular pigment. Older observers exhibited greater inter-, but not intra-observer, variability in their matches.

1. Introduction

Human color vision is a form of spectral analysis in which the three classes of cones, the long- (L-), middle- (M-) and short- (S-) wavelength sensitive cones with different spectral sensitivities, convert spectral power distributions (SPD) into three cone excitations. Consequently, lights can be specified colorimetrically simply in terms of the three cone excitations they produce. Any pair of lights that produce the same three cone excitations will appear identical even if their SPDs are different (such lights are known as metameric pairs).

Although specifying lights colorimetrically in terms of the three cone excitations is relatively simple, it is complicated by the fact that the three cone spectral sensitivities can vary between observers—even between observers with ostensibly normal color vision. Consequently, the specifications of lights in terms of the three cone excitations frequently differ between observers as a result of which pairs of lights that are metameric for one observer may not be metameric for another. Such discrepancies are known as observer metameric failures or observer metamerism. Being able to accurately predict observer metamerism and thus compensate for the effects of individual differences is becoming increasingly important in color measurement and color reproduction. The most accurate predictions require a knowledge of the cone spectral sensitivities of individual observers, the estimation of which is described below.

Variability in human cone spectral sensitivities occurs for a variety of reasons, including genetically determined spectral shifts in the L- or M-cone spectral sensitivities, variations in the L, M, or S photopigment optical densities, and differences in the densities of the lens and macular pigments (through which light must pass between the cornea and the photopigments, [for review

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see 1]). In addition, some factors, such as the density of the lens pigment, are age-dependent [2], meaning that the cone spectral sensitivities vary across the lifespan.

This paper is the third in a series of papers in which we ask observers to make sets of color matches from which we infer their individual cone spectral sensitivities and can thus estimate the individual differences between our observers. The principle behind this work is that triplets of lights of different wavelengths that are matched to the *same* white standard are metamers should all produce identical L-, M- and S-cone excitations. Consequently, we can adjust the three cone spectral sensitivities to find the triplet of spectral sensitivities that best fulfills this condition for a given observer. We found the optimal cone spectral sensitivities by applying an extended version of the model of LMS cone spectral sensitivities (known now as the CIEPO06 model) for 2° and 10° observers published by the CIE in 2006 [3] (and based almost entirely on work by Stockman, Sharpe & Fach [4] and Stockman & Sharpe [5]). The basic version of the LMS model also allows the macular and lens optical density spectra, and cone photopigment absorption spectra to be varied to account for age and field size. The extended version of the CIEPO06 LMS model formulated by Stockman & Rider [6] defines the cone sensitivities and other spectra as continuous functions of wavelength from 360 and 850 nm and enables spectral shifts of the M- and L-cone photopigments along a logarithmic wavelength scale. We use this extended model to find the photopigment, macular and lens optical densities and L- and M-cone photopigment spectral shifts that best account for an individual's color matches.

In our first paper [7], we introduced a new LED-based visual trichromator, called LEDMax, with which we obtained color matching data from five experienced color normal observers, each of whom made repeated matches between 11 triplets of LEDs of different wavelengths and a white standard for fields of 2 and 10° in visual diameter The inter- and intra-observer variabilities of the derived cone spectral sensitivities were found to be small. In the second paper, we extended this work to include an additional 46 young Chinese color normal observers [8]. Overall, the individual differences in the estimated cone spectral sensitivities were consistent with the standard or mean CIEPO06 observer except for a 3-nm shift of the M-cone photopigment to longer wavelengths and a slight increase in the 2-deg macular pigment density. The 51 observers had an average age of 24.3 years (range 19–31 years). The matches of 30 observers from that study, who used the same Lab matching method used here (see below), are also included in this study.

In this paper, we extend our work by adding 70 observers with normal color vision, who are younger and older than the observers from our first and second studies. Our goal was not only to increase the size of our cohort of observers but also to be able to assess the effects of ageing on color matches and cone spectral sensitivities. Ageing is known to cause poorer visual performance [9], poorer color discrimination [10–12] and lower cone sensitivities [13–16]. Changes in overall sensitivity that do not change the shapes of the cone spectral sensitivity functions should not affect most color matches (except perhaps for making them noisier because of the reduced sensitivity or limiting the spectral range over which they can be made). Other changes with age, such as the lens becoming yellower [2], will affect cone spectral sensitivities and thus color matches.

Humans maintain a degree of color constancy over life because of mechanisms that compensate for differential sensitivity losses, such as the yellowing caused by the ageing lens, so that we are often unaware of age-related changes [12,16]. These compensatory changes become readily apparent following a lens replacement cataract surgery after which it can take several weeks or months for colors to appear completely normal again [17].

Further motivation for this work is the urgent need not only for better standard or mean cone spectral sensitivities and CMFs but also for more reliable estimates of the effects of individual variability. This need has become more pressing with the recent advancements in display technologies and the introduction of narrowband primary lights that expand the color gamut

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(e.g., LCD, OLED, Mini-LED, QD-OLED and laser devices). Such narrowband lights typically accentuate the effects that individual differences in spectral sensitivities can have on color reproduction. Moreover, these difficulties are exacerbated by the continued use of the ubiquitous, yet fundamentally flawed, CIE 1931 2° observer, because it fails to accurately reproduce colors even for the mean normal observer particularly at shorter wavelengths [18–22].

In this paper, we define individual differences in terms of the variability of the best-fitting parameter values of the extended CIEPO06 model. From these, we can estimate the effect that each parameter has on the shapes of the cone spectral sensitivities. Importantly, these estimates of variability are biologically relevant, since they relate to the underlying causes of the individual differences.

2. Methods

2.1. Apparatus and procedure

We used a multi-LED visual trichromator for the color matching experiments, the details of which can be found in our previous paper [7]. Briefly, two multi-LED light sources separately illuminated two uniform, vertically abutting semi-circular half-fields, and the intensities of the LEDs making up each light source could be independently varied. Apertures were used to restrict the size of the resulting circular field to 2° or 10° fields of view (FOV).

The right-hand half-field was illuminated by three LEDs with dominant wavelengths of 640, 530, and 445 nm (chosen to be close to the RGB primaries used by Stiles and Burch [23]) that together produced a standard white with a correlated color temperature (CCT) of 7500 K and a luminance of 120 cd/m^2. The left-hand matching half-field was illuminated by one of the 11 triplets of LEDs listed in Table 1, one of which was the same triplet used for the white standard. The other ten triplets used one of ten unique LEDs combined with two of the standard LEDs, a procedure that is comparable to the procedure used in a traditional Maxwell method color matching experiment.

Table 1. The 11 different triplet sets for Mixture half-field. Note, the standard LEDs are shown in black text and the unique LEDs are in red

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

Observers adjusted the triplet of LEDs making up the matching half-field until they were satisfied that the matching half-field matched the reference white. To make the adjustments easier for color normal observers, the three LED lights in the matching half-field were transformed using the gain-offset-gamma (GOG) model [24] and polynomial fitting to XYZ tristimulus values, then further converted into the CIELAB space using standard CIE methods. The observer was

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then asked to vary Lightness, a* (redness-greenness), or b* (yellowness-blueness) to match the white standard. Color normal observers found these adjustments to be perceptually more intuitive and easier to perform than adjusting the intensities of the individual LEDs. We call this matching procedure the Lab matching method.

The matching experiment was conducted in a darkened environment to which the observers adapted for 2 minutes prior to the start of the experiment. A chinrest was used to maintain head position 50 cm from the stimulus and the fields were viewed binocularly. 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 color matches. The practice matches were not used in the analysis. In the main experiments, observers first made color matches for a FOV of 10°, until 15 random-order matches were completed (11 matches, one for each triplet in Table 1 and four repeats, see below). After a brief rest and re-adaptation, the observer then completed 15 further random-order sets of color matches for a 2° FOV (11 matches, one for each triplet and four repeats). The four repeats, which were made for triplets 2, 3, 6, and 10 (see Table 1), were included to estimate intra-observer variability. In total, each observer performed 30 color matches, which took on average about 60 minutes. Including adaptation and training time, the total duration of the experiment was approximately 90 minutes. Once the experiment was finished the SPDs of the standard reference and each of the matched lights were measured from the observer's eye position using a Konica-Minolta CS2000 spectroradiometer.

2.2. Observers

In total, 100 Chinese observers with normal color vision participated in this study. Their ages ranged from 8 to 80 years old. They were divided into seven groups mostly by decade as listed in Table 2. In our previous paper, two methods of adjusting the matching fields were used: adjusting the intensity of the R, G and B LEDs independently - the RGB method; and adjusting the LEDs together in approximately L*, a* and b* directions of CIELAB color space - the Lab method. The 30 observers from Group 2 are those who used the Lab method, as did all the other observers in the current study. All observers initially underwent Ishihara testing to exclude clearly color deficient observers with, of course, the LEDMax matches themselves providing further confirmation that their color vision was normal.

Table 2. Observer numbers in each age group (those in Group 2 are from our previous paper [8]).

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

3. Results

3.1. Color matching results

Figures 1 and 2 show the observers' 2° and 10° color matches, respectively, plotted in MacLeod-Boynton chromaticity coordinates for each age group. These coordinates are calculated using the

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CIEPO06 2° and 10° standard LMS cone spectral sensitivities. The white cross in each panel denotes the chromaticity co-ordinate of the reference field. The red dots denote each individual match, and the red ellipses show the 95% confidence ellipses for each age group (i.e., 95% of the data points should lie within the boundary of the ellipse). The black dots and black 95% confidence ellipses correspond to the coordinates calculated using the individually fitted cone fundamental CMFs, which will be described later. Note, however, that the individual differences in LMS CMFs for each observer mean that the reference white also varies in MacLeod-Boynton space. To simplify the comparisons between different observers, we have shifted the matches in Figs. 1 and 2 so that the white reference for each individual observer coincides with that of the CIEPO06 standard observer (white crosses).

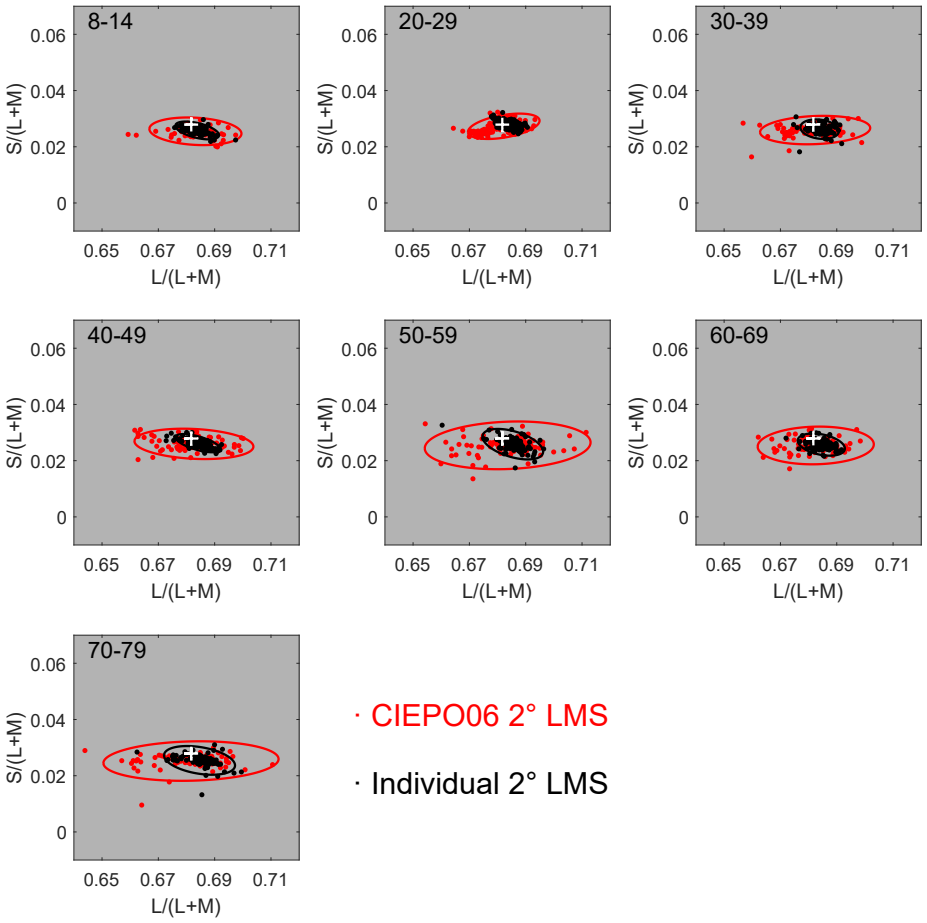

Fig. 1. 2° color matches for different age groups plotted in MacLeod-Boynton chromaticity space. Each dot represents a single match for a single observer. Red dots were calculated using the CIEPO06 standard observer CMFs, while the black dots were calculated from the individually fitted CMFs. Ellipses denote 95% confidence limits. The white crosses indicate the reference white for the CIEPO06 standard observer.

If all the observers in our study had the same cone spectral sensitivities as the CIEPO06 2° and 10° standard observers and their settings were perfect (error free), all the red points in Figs. 1 and 2 would fall on the white cross, corresponding to D75. Clearly, they do not, partly because of experimental error but also because of individual differences in the cone spectral sensitivities. Much of the variability between the matches seen in Figs. 1 and 2 shown by the red

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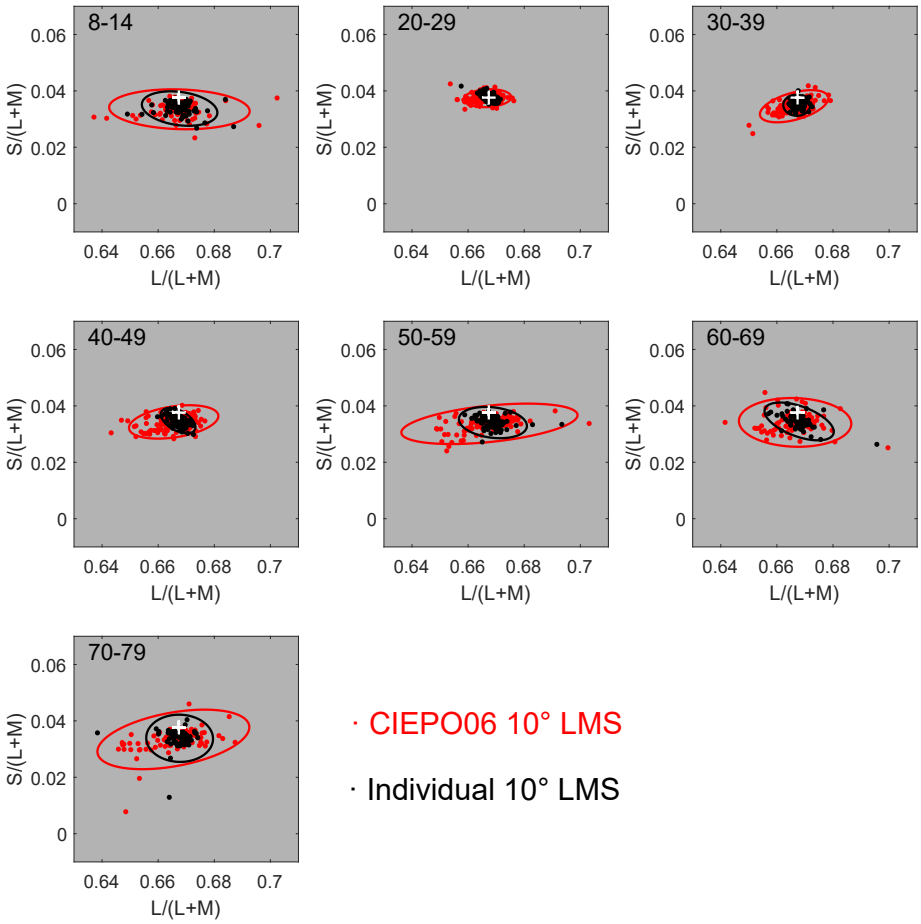

Fig. 2. 10° color matches for different age groups plotted in MacLeod-Boynton chromaticity space. Details as Fig. 2.

crosses seems to be in the L/(L + M) direction, which suggests individual differences in the L- and M-cone spectral sensitivities. The match variability is smallest for the 20-29 year age group and greatest for the older age groups. The intra-observer variability, calculated from the repeated matches, is roughly constant with age, while the inter-observer variability is somewhat higher for the youngest and the older age groups (see Table 3). The intra-observer variability reflects the repeatability and stability of the observer data with lower values showing better repeatability and more stable data. The inter-observer variability reflects the individual differences between the observer's color matches with the larger values showing greater variability. Thus, the spread of matches depends more on individual differences than on a age-dependent changes in the ability of observers to make reliable matches. In the next section, we analyze the causes of the individual differences and estimate the individual cone spectral sensitivities (the matches predicted by the individual functions are shown by the black dots in Figs. 1 and 2).

3.2. Derivation of individual cone spectral sensitivities

To determine the causes of the individual variability, we fitted the extended CIEPO06 [3] model of Stockman & Rider [6] simultaneously to the 2° and 10° FOV color matches for each observer. The model fitted to the 2° and 10° data has eleven parameters: the optical densities of the L-,

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Table 3. Observer variabilities in each age group.

Group	Mean inter-observer variation ($\Delta l_{mb} s_{mb} \times 10^{-3}$)		Mean intra-observer variation ($\Delta l_{mb} s_{mb} \times 10^{-3}$)	
FOV	2°	10°	2°	10°
1	4.38	5.42	1.09	1.34
2	2.81	3.35	1.02	1.13
3	3.74	3.04	1.23	1.01
4	3.83	3.05	1.26	1.02
5	5.30	5.16	1.76	1.71
6	4.46	4.35	1.48	1.45
7	5.32	5.09	1.79	1.66
Mean	4.26	4.21	1.38	1.33

M- and S-cones, denoted by l_{OD}, m_{OD} and s_{OD}, and the macular density, k_{mac}, for 2° and 10° (8 parameters); and the lens density, k_{lens}, and spectral shifts of the L and M cones L_{shift} and M_{shift} that are the same at 2° and 10° (3 parameters). We varied these 11 parameters to find the best-fitting values that minimized the squared differences between the L-, M- and S-cone excitations produced by the reference white spectrum and the 11 matched spectra for 2° and for 10° FOV.

Figures 3, 4 and 5 show the distributions of 11 fitted parameters as functions of age. Figure 3 shows the parameters that are common to the 2° and 10° matches, Fig. 4 those specific to the 2° matches and Fig. 5 those specific to the 10° matches. In Fig. 3, the M- and L-cone shifts unsurprisingly vary little with age but the M-cone spectral sensitivities are shifted compared to the CIE standard observer to longer wavelengths by on average 2.53 nm and the L-cone spectral sensitivities to shorter wavelengths by on average 1.97 nm (see Table 3). The lens densities as expected increase with age, but at a slightly slower rate (density at 400 nm increases by 0.0093 per year) compared to the initial slope of the CIEPO06 piecewise linear equations (0.0132 per year), shown as the black lines in Fig. 3, which are based on Pokorny, Smith & Lutze [2]. We find little evidence for the dramatic uptick in lens density reported after 60 years of age (0.0441 per year, shown as the steeper black line segment in Fig. 3). Unfortunately, due to an administrative oversight, no record was kept as to whether any of our older observers had received lens replacement surgery for cataracts. A future study will address this by measuring older observers with and without lens replacements.

The R^2 for the other parameters are close to zero except for the L-cone optical density parameter (l_{OD}) for both the 2° and 10° FOV matches, which seems to increase slightly with age. There is also a weaker negative trend for M-cone optical density. Although the R^2 values between age and the various parameters do not show a clear correlation, when we focus on the p-values, the p-values between age and parameters $L_{shift}(0.026)$, $M_{shift}(0.005)$, k_{lens}, l_{OD}, and m_{OD} (these three items are less than 1×10^{-5}) are all less than 0.05, indicating that there is indeed a significant correlation between these parameters and age. However, for parameters k_{mac}, the p-values with age are all greater than 0.05, meaning their relationship with age is not significant, while s_{OD} showed significant correlation with age only for the 10° FOV.

The mean best-fitting parameters are given in Table 4 and the best-fitting parameters for each individual observer are given in Table 6 in the Appendix.

We performed t-tests with Bonferroni correction that showed the mean L- and M-shifts were significantly different from CIEPO06 (p-values < 0.0001), as were the mean optical density of the M-cones for 2° and the L and S-cones for 10°, and the mean macular pigment density was significantly higher for both FOV. The means of the other cone optical densities and the mean

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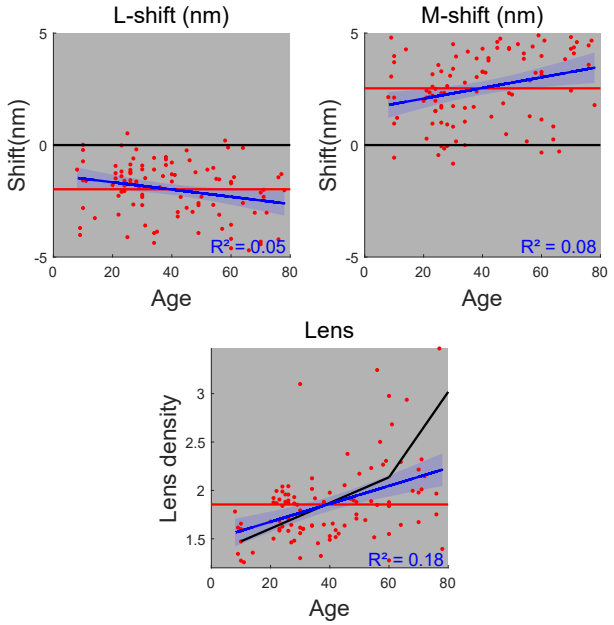

Fig. 3. The distribution of the 3 parameters against age that are common to the 2° and 10° matches. Red dots denote individual fitted parameters, black lines denote the CIEPO06 standard parameters, blue lines and shaded regions show the linear regression of our data and its 95% confidence intervals, red lines show mean fitted parameters.

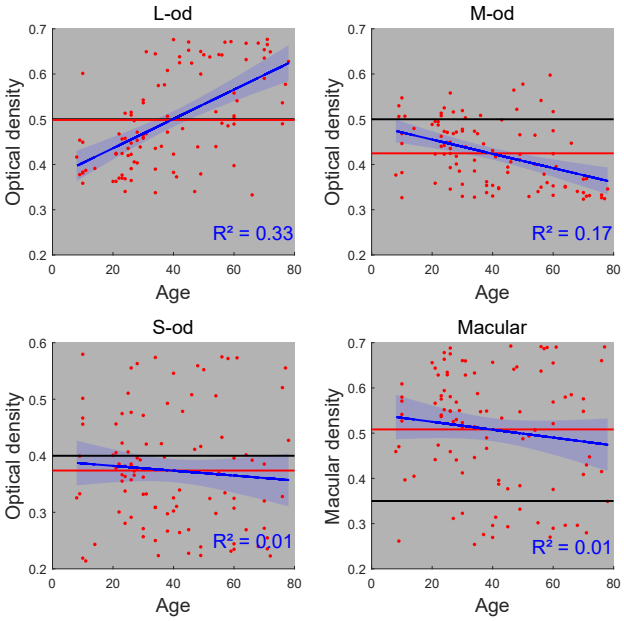

Fig. 4. The distribution of 4 vision parameters against age specific to the 2° matches. Details as Fig. 3.

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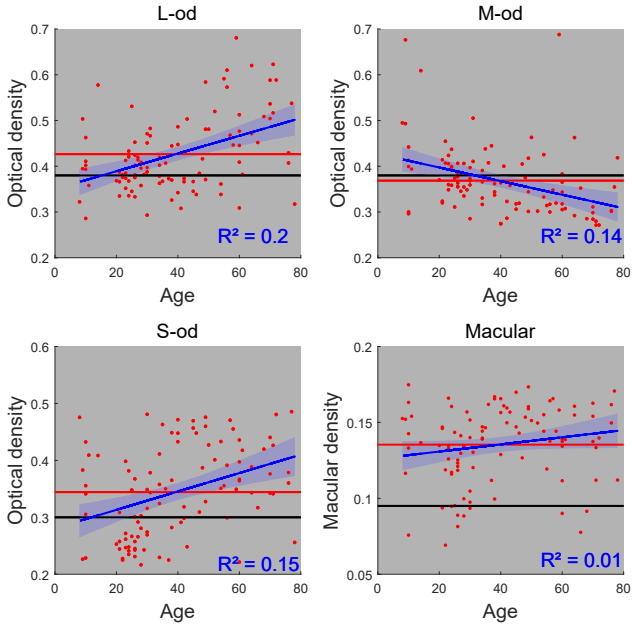

Fig. 5. The distribution of 4 vision parameters against age specific to the 10° matches. Details as Fig. 3.

Table 4. Summary of the means and standard deviations of the best-fitting parameters. The parameter lens gives the density of the lens pigment at 400 nm and mac the optical density of macular pigment at 460 nm.

				2°				10°			
	L_{shift}	M_{shift}	k_{lens}	l_{OD}	m_{OD}	s_{OD}	k_{mac}	l_{OD}	m_{OD}	s_{OD}	k_{mac}
Male	-1.97	2.57	1.82	0.50	0.46	0.39	0.48	0.43	0.37	0.33	0.131
(SD)	(1.31)	(1.56)	(0.39)	(0.10)	(0.07)	(0.11)	(0.16)	(0.08)	(0.08)	(0.08)	(0.024)
Female	-2.01	2.49	1.88	0.50	0.38	0.35	0.53	0.43	0.37	0.35	0.139
(SD)	(1.17)	(1.54)	(0.43)	(0.11)	(0.06)	(0.10)	(0.11)	(0.09)	(0.07)	(0.08)	(0.026)
Mean	-1.97	2.53	1.85	0.50	0.42	0.37	0.51	0.43	0.37	0.34	0.135
(SD)	(1.24)	(1.55)	(0.41)	(0.11)	(0.07)	(0.10)	(0.13)	(0.08)	(0.07)	(0.08)	(0.025)
CIEPO06	0	0	1.76	0.50	0.50	0.40	0.35	0.38	0.38	0.30	0.095

lens density did not differ significantly from the CIEPO06 standards ($p > 0.05/11$). Two-sample t-tests (with Bonferroni correction) confirmed there were no significant differences between the male and female observers for any of the parameters.

We then used the fitted LMS CMFs to estimate the triplets in MacLeod-Boynton chromaticity coordinates that match the white standard, adjusted so that the reference for each individual coincides with that of the CIEPO06 standard observer. These are shown by the black dots and ellipses in Figs. 1 and 2. The improvements in the match predictions can be seen by comparing these with the red dots and ellipses that were derived using the CIEPO06 standard observer. As can be seen, the scatter is much reduced. For the CIEPO06 standard 2° and 10° LMS, the averaged distance from each point to the mean in $\Delta l_{mb} s_{mb}$ are 5.55 and 5.40×10^{-3}, respectively. For the individual 2° and 10° LMS, the average distances from each point to the mean are 2.98 and 2.70×10^{-3}, respectively. The average distance from the mean of all the matches in each

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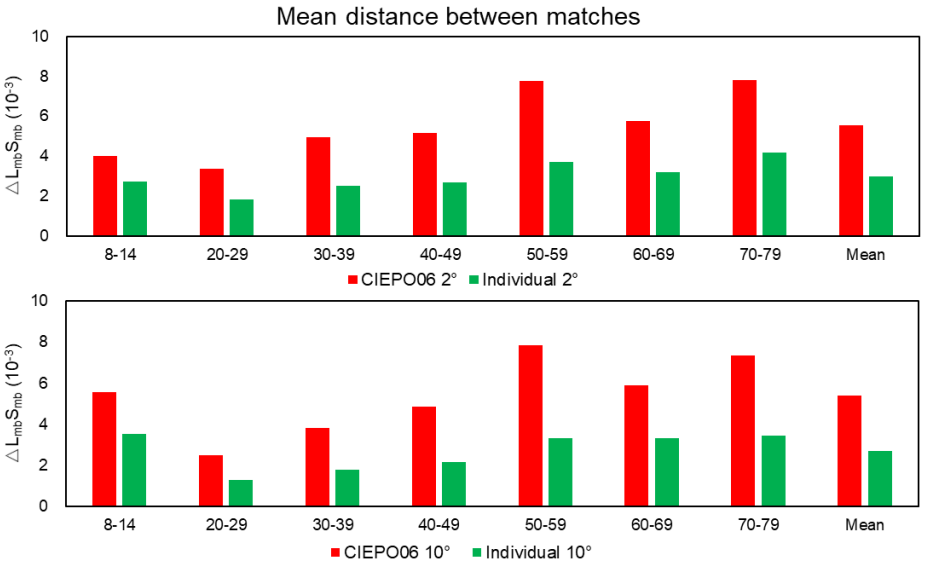

Fig. 6. The averaged distance from each mean of all individual's matches in MacLeod-Boynton space calculated using the CIEPO06 standard (red) or the individual CMFs (green).

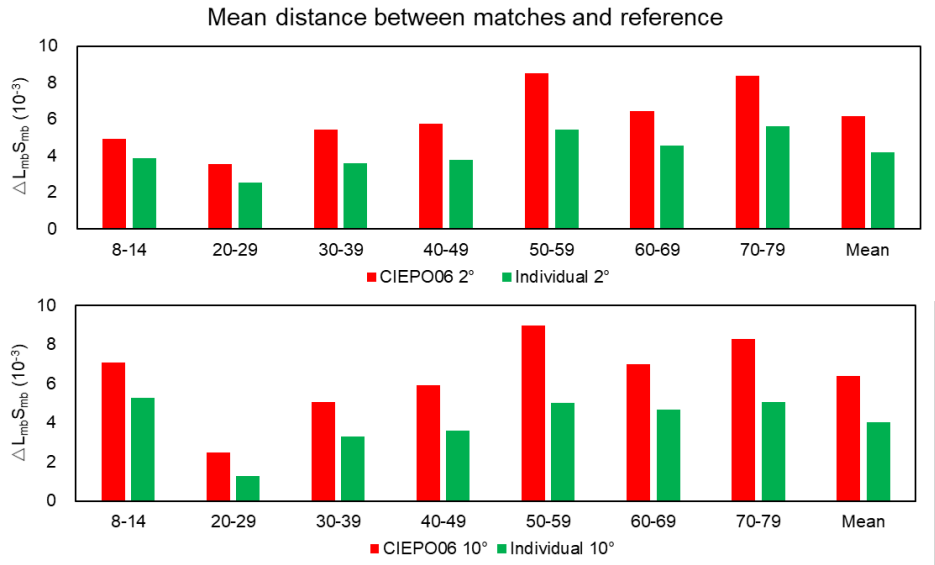

Fig. 7. The mean differences between the matches and the white reference in MacLeod-Boynton space calculated using the CIEPO06 standard (red) or the individual CMFs (green).

age group are shown in Fig. 6. The red bars denote the differences using the CIEPO06 standard observer model and the green bars are the individual CMFs. Note, this ignores the reference white and simply examines the variability of the matches. It can be seen in Figs. 1 and 2 that the centers of the clusters and ellipses do not always coincide with the reference (white cross), suggesting the standard observer and individual CMFs both fail to accurately predict the appearance of the reference. Figure 7 shows the mean distances of each match compared to the reference white

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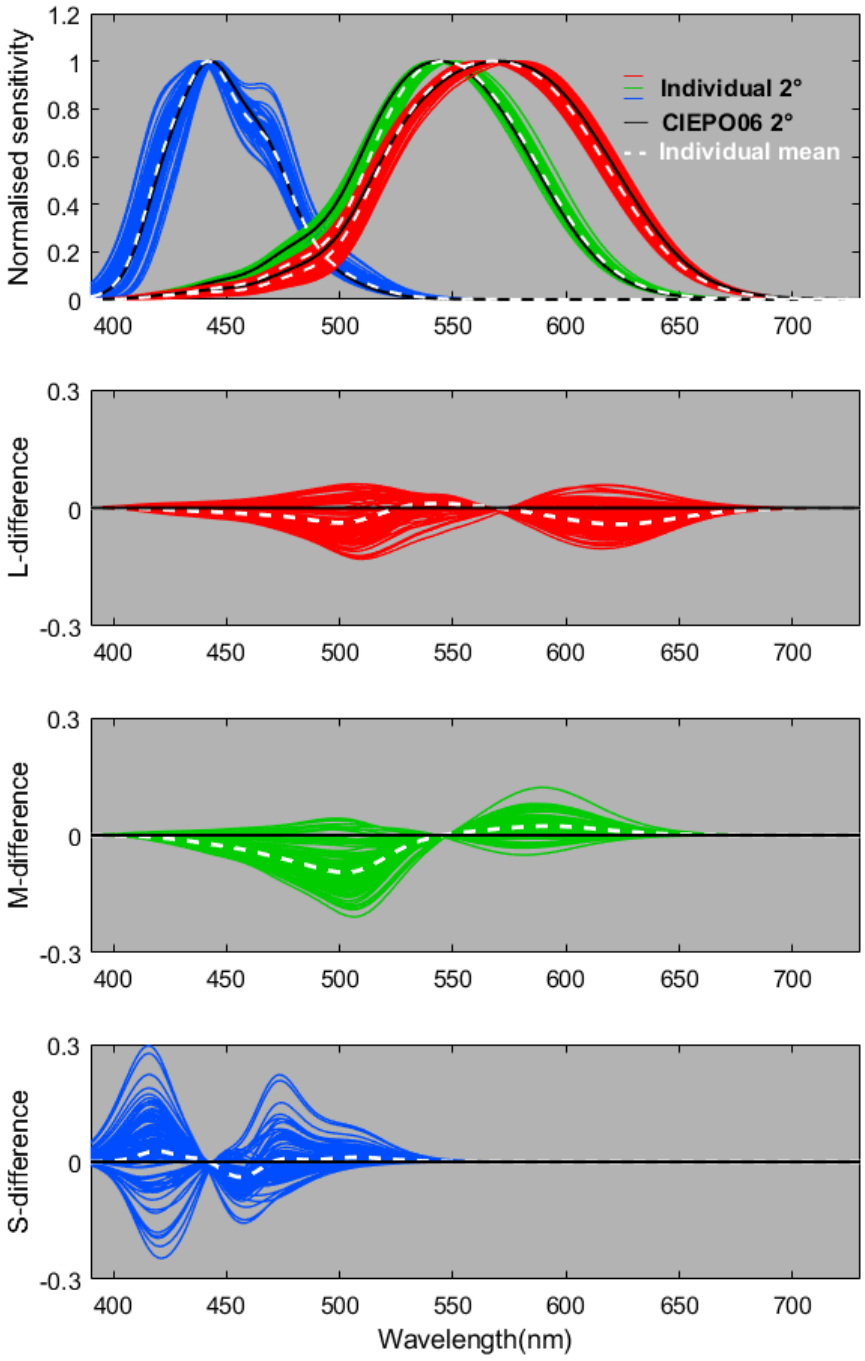

Fig. 8. Upper: Observers' 2° cone fundamentals. Red, green and blue curves denote L-, M- and S-cone fundamentals, respectively. Solid black curves denote CIEPO06 2° cone fundamentals. The dashed white line shows the means of the individual spectral sensitivities. Lower: Differences between the CIEPO06 2° cone fundamentals (solid line) and the individual functions (colored lines). The means of the individual functions are shown by the white dashed lines.

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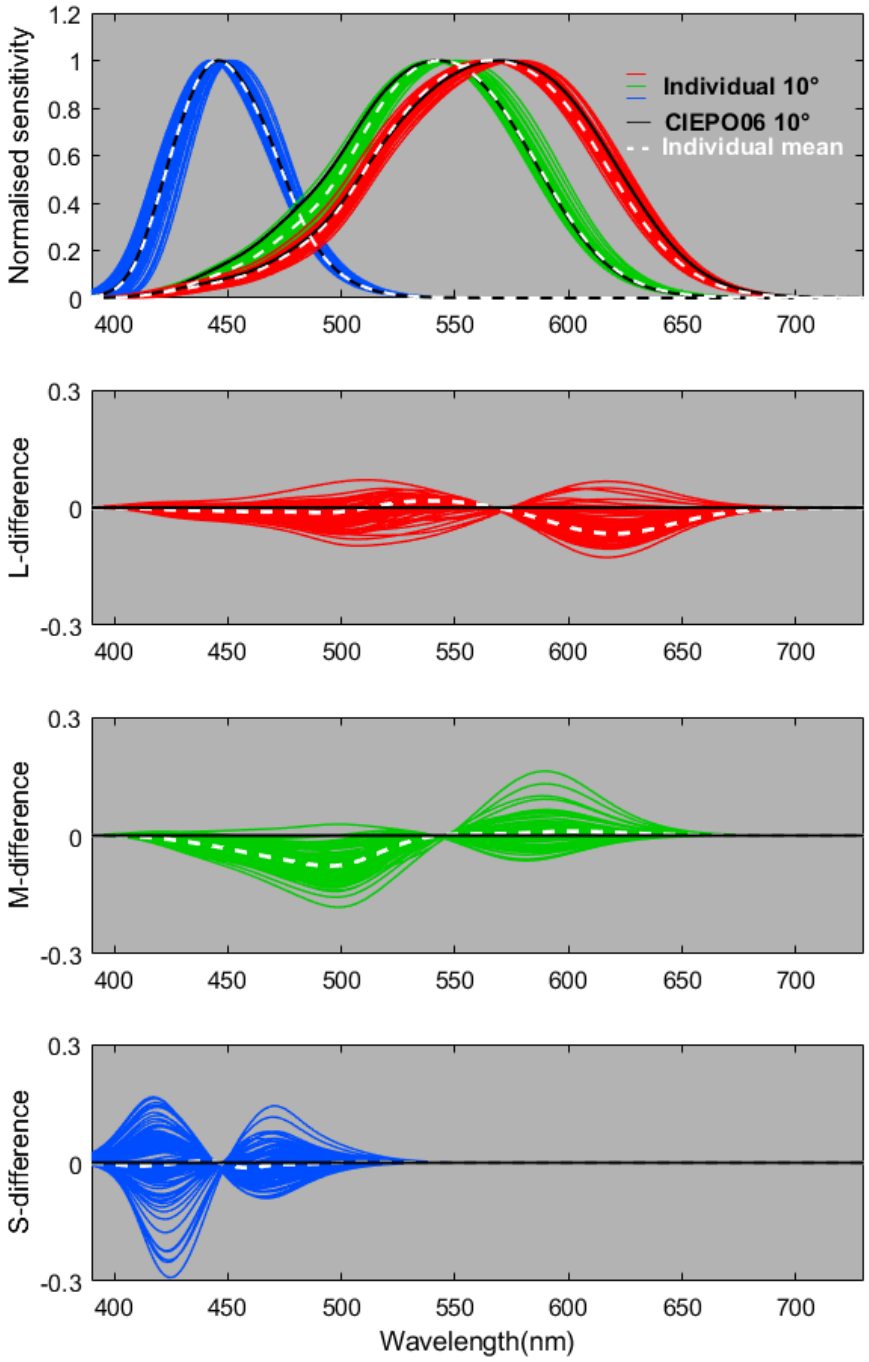

Fig. 9. Details as Fig. 8 but for 10° cone fundamentals.

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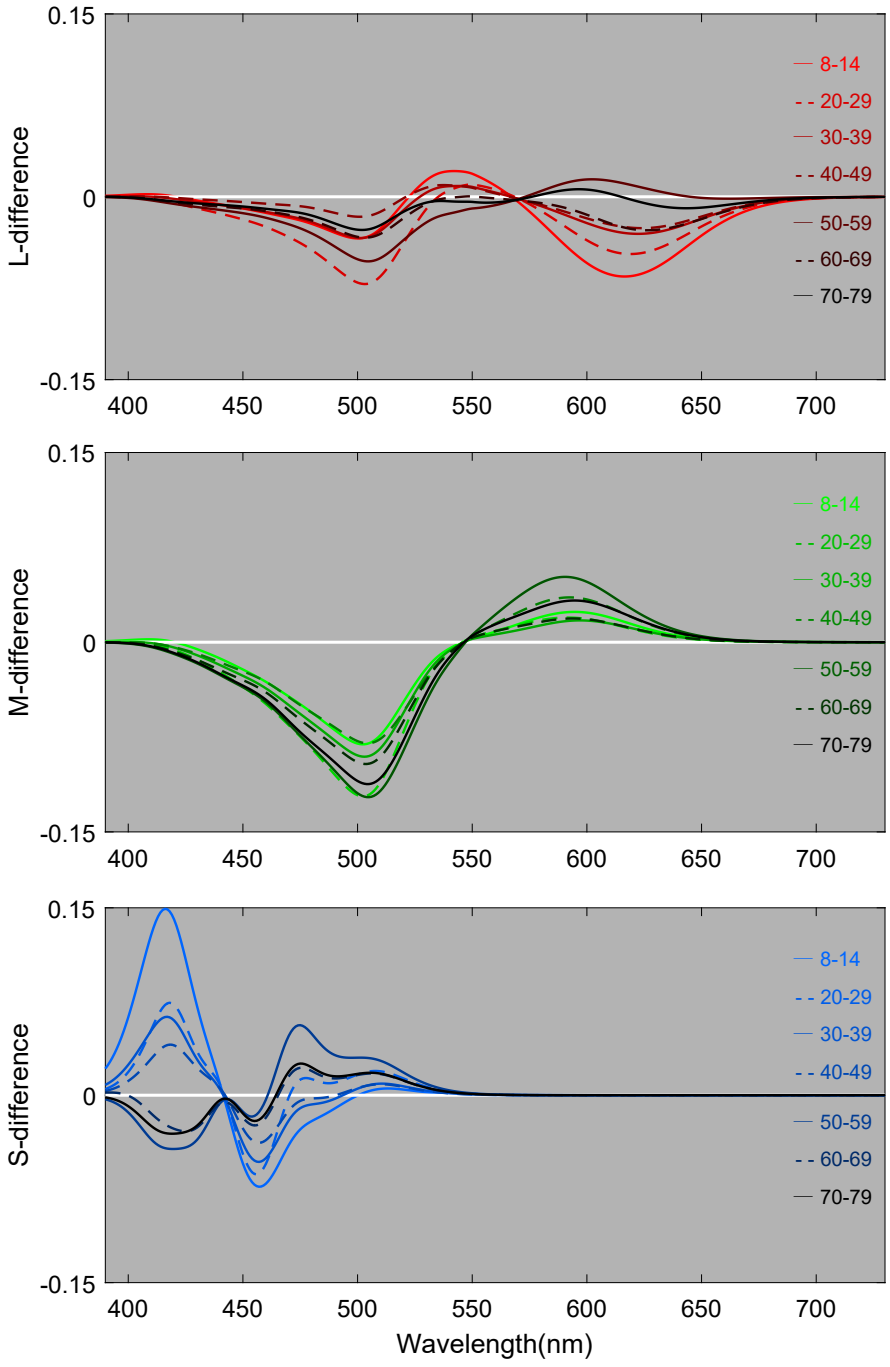

Fig. 10. The difference between observers' 2° mean cone fundamentals and CIEPO06 2° cone fundamentals (solid white line). Red, green and blue curves denote L-, M- and S-cone fundamentals, respectively, plotted as a function of age (see key).

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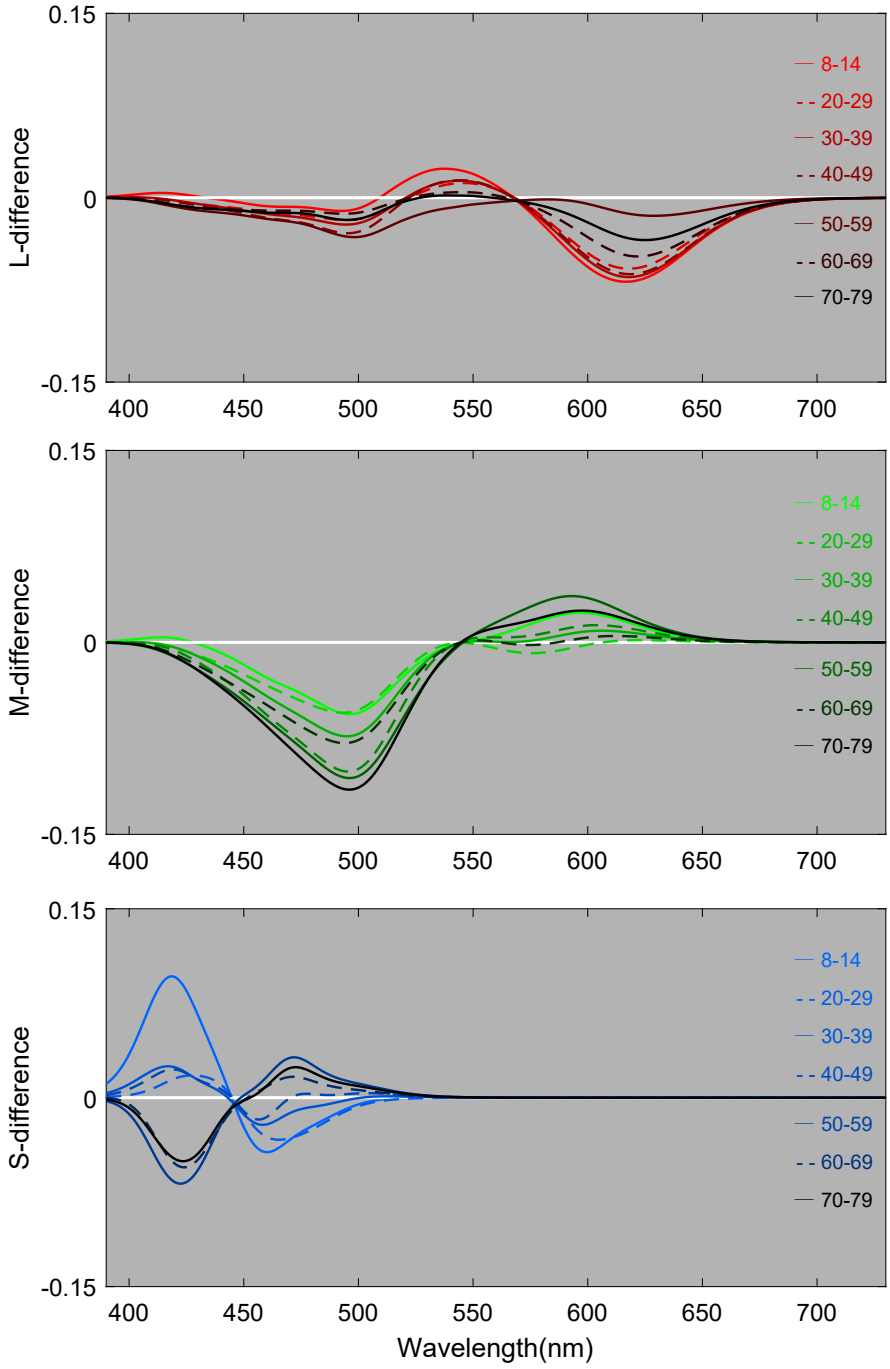

Fig. 11. Details as Fig. 10 but for 10° cone fundamentals.

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under the CIEPO06 standard observer and the individual CMFs. The pattern is very similar to Fig. 6, with the individual CMFs producing much smaller errors than CIEPO06, but overall the distances are slightly larger.The mean differences for the 2° and 10° observers are shown by the rightmost pair of bars in Figs. 6 and 7.

As expected, the match predictions for the individually determined LMS functions are always substantially better than the prediction of the mean CIEPO06 LMS functions.

The 100 individually derived cone fundamentals for 2° and 10° FOV are shown in Figs. 8 and 9, respectively. Cone fundamentals are the sensitivity of the cones with respect to light at the cornea, and so includes the effects of lens and macular pigment as well as the optical density and spectral position of the photopigments themselves. The top panels in each figure show the individual estimates of the L-, M- and S-cone fundamentals. The means of the individual estimates are shown by the white dashed lines. For comparison, the black curves are the CIEPO06 2° or 10° standard curves. The three lower panels in each figure show the differences between the individual curves and the CIEPO06 standards. The mean 2° and 10° LMS CMFs from our study are given in Table 5 of the Appendix in 10 nm steps.

The changes in sensitivity between individuals can be quite large: up to about ±0.3 at short wavelengths for S-cones, about ±0.2 for M-cones at around 500 and 600 nm, and about ±0.1 for L-cones at around 520 and 620 nm. The larger differences in S-cone fundamentals reflect the fact that the biggest variability comes from lens and macular pigment and these have most effect at short wavelengths.

The population variability shown in Figs. 8 and 9 hides the differences that are found with age. These can be seen more clearly in Figs. 10 and 11 in which differences for different age groups are plotted.

The effect of lens density is readily apparent in the 10° S-cone fundamentals (lower panel of Fig. 11) where the younger age groups are relatively more sensitive to short wavelengths and less sensitive to longer, while the opposite is true for the older age groups. The more complicated waveforms in the 2° S-cone fundamentals (lower panel of Fig. 10) are the combination of age-related lens density changes combined with an overall increase in macular pigment density in our subjects compared to the population represented by the CIEPO06 functions.

The M-cone lower sensitivity near 500 nm and higher sensitivity near 600 nm (for 2° and 10° FOV) can be explained by the spectral shift in our subjects. The increase in lens density is again apparent as greater reductions in sensitivity at 500 nm with age. The opposite trend appears to hold for L-cones.

4. Conclusions

In this paper, we extended our earlier work [7,8] by asking a further 70 observers with normal color vision, who were younger and older than our original observers, to make color matches using the LEDMax trichromator. Our goal was to increase the overall number of observers and also to investigate the effects of ageing on color matches and cone spectral sensitivities.

We estimated each observer's photopigment, macular and lens optical densities and their L- and M-cone photopigment spectral shifts, and thus obtained their individual cone spectral sensitivities. The average individual differences across observers were found to differ somewhat from the CIEPO06 standard or mean observer, but with +2.53 and -1.97 nm shifts of the M- and L-cone photopigments, respectively, and a 43-45% denser 2-deg macular pigment density, as well as slight differences in some cone optical densities. There was a gradual increase in lens density with age and unexpectedly a small increase in L-cone optical density, but other factors showed relatively little correlation with age. Older observers showed more inter-observer variability, but intra-observer variability was relatively fixed across the age span. Although increases in L- and M-cone optical densities with age have been reported by Renner *et. al* [25], we find no evidence for an increase in M-cone optical density with age and in fact there is a non-significant negative

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trend in our fits. We suspect some of the small, unexpected changes in optical density, such as the increase in L-cone optical density with age, might be an artefact of the fitting procedure resulting from discrepancies in the shape of the lens template assumed in CIEPO06. Furthermore, in our previous study [8] we found that several parameters were strongly correlated in the fits, including lens density, L- and M-cone spectral shifts and L- and M-cone optical densities.

One difference to note from the previous analysis of 51 young Chinese color normal observers presented in our last paper [8] is that there is now a consistent but small shift of the L-cone photopigment to shorter wavelengths by about 2 nm. In our previous modelling, the limits of how much the parameters could vary were in some cases too low, particularly for macular pigment density and S-cone optical density. These constraints on the parameter-space produced slightly suboptimal fits. The analysis here allowed the parameters to vary more widely and thus produce better fits to the data and more reliable cone fundamentals.

The parameter estimates we found suggest that for our population of observers, small adjustments to the CIEPO06 LMS and CIE 2015 XYZ CMFs, particularly to the L- and M-cone peak sensitivities, and to the macular pigment density better predict their color matches. Further verification of our methodology and model will require measurements such as cone spectral sensitivities, color matches, and lens and macular densities preferably using monochromatic lights, as well as a molecular genetic analysis of the observer's photopigment genes, but these are beyond the scope of this study. Nevertheless, we have shown that the use of individual CMFs significantly reduces the matching errors predicted by standard CMFs. Such individualized specifications will be important for color critical applications, but we note that more appropriate metrics for quantifying color differences for individual observers are required.

If we are to usefully relate these individual differences in cone spectral sensitivities to differences in color appearance, then models of color appearance that explicitly link color appearance to the L-, M- and S-cone spectral sensitivities will be required. Most current appearance models have been manipulated and adjusted to predict color differences using the flawed 1931 XYZ CMFs and are therefore inappropriate for LMS cone spectral sensitivities. If instead of comparing the matches by evaluating the implied cone excitations, as in Figs. 6 and 7, we calculate the color appearance differences between them, the individual fits outperform those of the CIE 1931 standard observer, but they do so by much less that would be expected from the improvements seen in Figs. 6 and 7. Unfortunately, color difference metrics in ΔE_{00} units cannot be usefully calculated from LMS data because they require individualized XYZ CMFs, and strictly speaking there is no such no such thing as individual XYZ CMFs. Thus, comparisons using ΔE_{00} units are at best only approximations. The mean color difference of all the matches for the standard observer was 9.01 and 9.13 ΔE_{00} for the 2° (CIE 1931) and 10° (CIE 1964) CMFs, while the individual CMFs gave values of 7.02 and 6.30 for 2° and 10°, respectively. A more realistic comparison of color differences from the LMS cone spectral sensitivities will require versions of CIELAB and ΔE_{00} formulae that are explicitly linked to, and optimized for, the CIEPO06 2° and 10° LMS CMFs rather than the CIE 1931 XYZ CMFs.

We will address other ways of representing individual variability, such as the definition of standard deviate observers or categorical observers, in a future paper.

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Appendix

Table 5. The averaged LMS data of 100 observers.

Wavelength (nm)	2°			10°		
	$\bar{l}$	$\bar{m}$	$\bar{s}$	$\bar{l}$	$\bar{m}$	$\bar{s}$
380	0.0003	0.0002	0.0013	0.0001	0.0001	0.0008
390	0.0008	0.0007	0.0152	0.0008	0.0007	0.0092
400	0.0027	0.0024	0.0671	0.0030	0.0027	0.0444
410	0.0082	0.0076	0.2423	0.0099	0.0095	0.1764
420	0.0173	0.0179	0.5496	0.0235	0.0252	0.4511
430	0.0263	0.0313	0.8136	0.0406	0.0500	0.7549
440	0.0369	0.0495	0.9872	0.0599	0.0833	0.9609
450	0.0462	0.0667	0.9311	0.0817	0.1224	0.9809
460	0.0609	0.0899	0.7875	0.1115	0.1706	0.8477
470	0.0938	0.1365	0.6525	0.1578	0.2374	0.6327
480	0.1344	0.1892	0.4215	0.2184	0.3169	0.3876
490	0.1840	0.2495	0.2265	0.2968	0.4131	0.2035
500	0.2800	0.3663	0.1250	0.4078	0.5448	0.0995
510	0.4433	0.5607	0.0695	0.5486	0.7041	0.0460
520	0.6285	0.7676	0.0344	0.6895	0.8486	0.0198
530	0.7820	0.9169	0.0150	0.8082	0.9486	0.0081
540	0.8879	0.9886	0.0060	0.8988	0.9954	0.0032
550	0.9568	0.9939	0.0023	0.9616	0.9883	0.0012
560	0.9905	0.9357	0.0009	0.9939	0.9249	0.0005
570	0.9975	0.8282	0.0003	0.9959	0.8127	0.0002
580	0.9758	0.6831	0.0001	0.9664	0.6654	0.0001
590	0.9193	0.5192	0.0001	0.9011	0.5022	0.0000
600	0.8217	0.3595	0.0000	0.7957	0.3458	0.0000
610	0.6872	0.2264	0.0000	0.6569	0.2169	0.0000
620	0.5338	0.1312	0.0000	0.5040	0.1254	0.0000
630	0.3834	0.0711	0.0000	0.3582	0.0679	0.0000
640	0.2529	0.0365	0.0000	0.2343	0.0348	0.0000
650	0.1530	0.0180	0.0000	0.1410	0.0171	0.0000
660	0.0860	0.0086	0.0000	0.0790	0.0082	0.0000
670	0.0453	0.0041	0.0000	0.0415	0.0039	0.0000
680	0.0228	0.0019	0.0000	0.0208	0.0018	0.0000
690	0.0111	0.0009	0.0000	0.0101	0.0009	0.0000
700	0.0053	0.0004	0.0000	0.0048	0.0004	0.0000
710	0.0025	0.0002	0.0000	0.0023	0.0002	0.0000
720	0.0012	0.0001	0.0000	0.0011	0.0001	0.0000
730	0.0006	0.0000	0.0000	0.0005	0.0000	0.0000
740	0.0003	0.0000	0.0000	0.0003	0.0000	0.0000
750	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000
760	0.0001	0.0000	0.0000	0.0001	0.0000	0.0000
770	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
780	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

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Table 6. The individual parameter of 100 observers.

Age	Sex	l_{shift}	m_{shift}	$lens$	$l_{od}2°$	$m_{od}2°$	$s_{od}2°$	$mac2°$	$l_{od}2°$	$m_{od}10°$	$s_{od}10°$	$mac2°$
8	F	-1.1	2.1	1.78	0.42	0.38	0.33	0.46	0.32	0.49	0.48	0.153
9	F	-3.7	3.1	1.34	0.45	0.51	0.40	0.47	0.39	0.49	0.23	0.117
9	M	-4.0	4.8	1.62	0.38	0.53	0.33	0.26	0.50	0.68	0.38	0.152
10	F	-0.7	4.0	1.58	0.60	0.33	0.50	0.58	0.41	0.30	0.43	0.163
10	F	0.0	-0.6	1.47	0.38	0.55	0.46	0.53	0.39	0.44	0.36	0.076
10	F	-0.2	1.0	1.66	0.38	0.38	0.58	0.54	0.29	0.30	0.31	0.175
10	F	-2.8	2.1	1.60	0.45	0.47	0.47	0.57	0.40	0.41	0.23	0.133
10	M	-1.6	3.7	1.27	0.36	0.45	0.22	0.61	0.46	0.40	0.34	0.143
11	F	-1.6	1.2	1.26	0.39	0.51	0.21	0.40	0.36	0.39	0.41	0.154
14	M	-3.3	4.3	1.36	0.39	0.48	0.24	0.40	0.58	0.61	0.41	0.137
20	F	-1.8	2.0	1.68	0.36	0.49	0.40	0.66	0.37	0.37	0.25	0.135
21	M	-1.3	2.4	1.88	0.42	0.36	0.46	0.64	0.37	0.32	0.26	0.147
21	F	-1.5	2.1	1.92	0.42	0.42	0.38	0.57	0.34	0.41	0.24	0.146
21	M	-0.9	0.3	1.50	0.36	0.50	0.41	0.44	0.39	0.32	0.31	0.094
22	M	-3.1	2.4	1.87	0.47	0.49	0.39	0.47	0.38	0.45	0.23	0.119
22	F	-2.3	2.1	1.99	0.37	0.49	0.30	0.63	0.38	0.41	0.23	0.069
23	F	-1.2	1.0	1.91	0.46	0.46	0.42	0.58	0.39	0.41	0.25	0.135
23	F	-2.1	2.6	1.69	0.37	0.51	0.47	0.54	0.35	0.42	0.27	0.166
23	M	-1.4	2.2	1.59	0.38	0.51	0.37	0.58	0.37	0.35	0.26	0.126
23	M	0.0	3.2	1.60	0.42	0.44	0.36	0.54	0.41	0.36	0.40	0.133
24	F	-1.8	1.5	1.99	0.46	0.44	0.28	0.59	0.43	0.36	0.25	0.095
24	M	-2.1	2.5	1.84	0.37	0.47	0.36	0.66	0.34	0.40	0.24	0.117
24	F	-1.8	1.5	1.63	0.51	0.42	0.38	0.55	0.42	0.44	0.38	0.116
24	F	-1.6	2.0	2.04	0.34	0.53	0.34	0.68	0.37	0.40	0.23	0.160
25	M	-4.1	3.6	1.96	0.44	0.45	0.51	0.63	0.35	0.31	0.27	0.143
25	M	0.5	-0.4	1.88	0.42	0.47	0.41	0.63	0.53	0.37	0.35	0.095
26	F	-1.6	1.7	2.04	0.36	0.56	0.56	0.68	0.42	0.36	0.24	0.125
26	M	-1.7	2.3	1.87	0.39	0.39	0.29	0.55	0.33	0.36	0.24	0.118
26	F	-1.3	1.7	1.71	0.42	0.45	0.36	0.46	0.40	0.38	0.23	0.081
26	F	-1.1	3.3	1.90	0.52	0.35	0.48	0.69	0.38	0.36	0.30	0.121
26	M	-0.9	-0.1	1.58	0.51	0.44	0.38	0.55	0.45	0.41	0.37	0.123
26	F	-1.2	1.0	1.96	0.45	0.42	0.39	0.58	0.38	0.38	0.26	0.089
27	M	-2.7	2.3	1.64	0.41	0.52	0.37	0.53	0.41	0.35	0.29	0.141
27	F	-0.6	-0.2	1.46	0.50	0.47	0.37	0.31	0.42	0.39	0.27	0.130
28	M	-1.6	0.9	1.87	0.47	0.47	0.40	0.53	0.40	0.41	0.30	0.134
28	M	-0.2	0.0	1.48	0.45	0.42	0.56	0.44	0.41	0.34	0.22	0.100
28	F	-1.7	2.6	1.93	0.40	0.40	0.38	0.57	0.36	0.35	0.28	0.088
29	F	-1.9	3.1	1.85	0.44	0.39	0.39	0.55	0.38	0.35	0.24	0.157
30	M	-2.2	0.8	1.79	0.47	0.52	0.47	0.51	0.40	0.40	0.27	0.093
30	M	-2.7	-0.8	1.56	0.46	0.47	0.27	0.41	0.39	0.37	0.35	0.097
30	M	-1.1	1.7	1.30	0.54	0.48	0.26	0.52	0.47	0.36	0.27	0.105

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30	M	-2.3	3.4	1.62	0.54	0.33	0.33	0.32	0.29	0.37	0.32	0.152
30	F	-0.9	4.5	3.10	0.46	0.36	0.36	0.66	0.45	0.29	0.48	0.140
31	F	-1.5	0.2	1.60	0.47	0.50	0.42	0.66	0.47	0.41	0.34	0.120
31	F	-3.6	4.0	1.60	0.65	0.44	0.33	0.63	0.48	0.51	0.38	0.130
34	M	-4.4	1.0	2.13	0.44	0.39	0.31	0.51	0.38	0.32	0.36	0.144
34	M	-0.6	2.8	1.64	0.64	0.33	0.31	0.45	0.40	0.33	0.41	0.140
34	F	-1.1	1.7	1.64	0.39	0.41	0.57	0.63	0.36	0.37	0.23	0.139
34	F	-3.9	0.0	2.02	0.34	0.47	0.25	0.25	0.42	0.39	0.32	0.147
35	M	-3.9	4.2	1.92	0.57	0.47	0.22	0.59	0.37	0.44	0.46	0.147
36	M	-1.9	2.5	1.45	0.44	0.51	0.42	0.55	0.41	0.41	0.35	0.162
37	F	-1.4	1.7	1.32	0.58	0.45	0.40	0.28	0.37	0.44	0.22	0.112
38	M	-0.5	2.4	1.88	0.61	0.36	0.30	0.49	0.44	0.34	0.28	0.100
38	M	-0.6	3.0	1.88	0.51	0.34	0.27	0.47	0.33	0.36	0.37	0.167
38	F	-0.9	3.9	1.65	0.47	0.35	0.49	0.55	0.37	0.34	0.45	0.166
40	M	-0.8	3.3	1.49	0.38	0.43	0.30	0.27	0.34	0.36	0.43	0.129
40	F	-1.6	3.3	1.98	0.42	0.35	0.55	0.66	0.45	0.27	0.47	0.166
40	M	-1.3	4.3	1.53	0.68	0.33	0.33	0.30	0.49	0.27	0.45	0.156
41	F	-1.3	3.2	1.66	0.37	0.42	0.31	0.31	0.31	0.40	0.29	0.161
42	F	-3.0	3.9	1.52	0.62	0.35	0.26	0.39	0.37	0.32	0.30	0.159
42	M	-3.2	3.8	1.59	0.64	0.35	0.34	0.40	0.37	0.29	0.32	0.150
43	F	-2.3	1.3	1.55	0.48	0.50	0.48	0.53	0.50	0.36	0.25	0.157
45	F	-0.2	4.3	2.05	0.65	0.39	0.23	0.38	0.35	0.31	0.47	0.170
45	F	-2.8	4.6	1.64	0.67	0.38	0.27	0.29	0.37	0.32	0.46	0.147
46	F	-0.7	4.7	2.38	0.62	0.41	0.51	0.69	0.34	0.32	0.45	0.143
47	F	-3.0	1.9	1.91	0.34	0.56	0.41	0.64	0.38	0.40	0.31	0.127
48	F	-1.2	0.5	1.90	0.44	0.52	0.56	0.65	0.42	0.38	0.39	0.153
49	M	-2.7	2.3	1.71	0.38	0.47	0.42	0.55	0.37	0.42	0.46	0.159
49	F	-2.6	4.3	1.75	0.65	0.42	0.24	0.33	0.48	0.34	0.33	0.160
49	M	-3.9	4.3	1.88	0.60	0.41	0.22	0.38	0.58	0.30	0.48	0.173
50	M	-2.3	2.3	2.17	0.64	0.58	0.55	0.49	0.48	0.46	0.43	0.151
52	F	-1.1	4.5	1.69	0.64	0.33	0.32	0.49	0.52	0.30	0.40	0.150
54	F	-1.0	3.9	2.23	0.44	0.46	0.51	0.51	0.36	0.43	0.35	0.144
54	M	-2.7	4.1	1.89	0.52	0.40	0.30	0.51	0.34	0.33	0.43	0.155
55	M	-1.5	0.2	1.52	0.64	0.34	0.37	0.30	0.59	0.31	0.36	0.119
56	F	-1.5	1.3	3.24	0.49	0.54	0.57	0.69	0.57	0.32	0.30	0.138
56	F	-3.1	2.9	1.85	0.64	0.35	0.43	0.64	0.61	0.30	0.39	0.164
57	M	-3.7	4.4	2.50	0.67	0.38	0.33	0.69	0.47	0.35	0.47	0.166
58	F	0.2	3.2	2.27	0.49	0.36	0.57	0.69	0.45	0.32	0.46	0.144
59	M	-0.1	4.9	2.31	0.67	0.60	0.23	0.27	0.68	0.69	0.35	0.158
60	F	-3.6	3.3	1.55	0.56	0.47	0.32	0.29	0.48	0.37	0.40	0.134
60	F	-4.2	1.1	1.28	0.40	0.52	0.23	0.66	0.51	0.38	0.22	0.090
60	F	-1.6	4.0	1.84	0.50	0.33	0.40	0.57	0.41	0.32	0.37	0.139

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60	F	-1.7	-0.3	2.98	0.49	0.42	0.31	0.52	0.45	0.34	0.36	0.112
60	M	-4.6	3.1	1.88	0.51	0.35	0.24	0.38	0.31	0.31	0.44	0.137
61	M	-1.4	4.7	2.68	0.54	0.40	0.57	0.69	0.38	0.31	0.42	0.139
64	M	-2.6	0.8	1.64	0.63	0.35	0.27	0.30	0.47	0.46	0.39	0.155
64	M	-0.1	0.3	2.29	0.67	0.35	0.40	0.58	0.62	0.29	0.34	0.161
66	M	-4.7	-0.3	2.94	0.33	0.45	0.39	0.59	0.45	0.35	0.32	0.078
68	M	-3.0	3.8	2.00	0.67	0.34	0.24	0.30	0.51	0.29	0.42	0.091
70	F	-4.4	4.8	1.67	0.65	0.34	0.27	0.41	0.59	0.28	0.44	0.154
70	F	-4.3	4.3	1.98	0.64	0.37	0.39	0.55	0.50	0.30	0.38	0.163
70	F	-2.1	2.4	2.21	0.59	0.32	0.32	0.58	0.54	0.31	0.34	0.137
71	F	-2.3	4.1	2.32	0.67	0.33	0.25	0.43	0.52	0.28	0.34	0.112
71	M	-2.0	4.4	2.01	0.68	0.37	0.24	0.28	0.62	0.27	0.43	0.133
72	M	-3.0	4.6	2.15	0.65	0.33	0.22	0.45	0.59	0.27	0.48	0.140
76	M	-1.4	3.6	1.75	0.54	0.33	0.33	0.42	0.41	0.30	0.38	0.162
76	M	-4.2	4.4	1.97	0.49	0.33	0.52	0.66	0.43	0.30	0.36	0.150
77	F	-1.3	4.7	3.47	0.58	0.32	0.56	0.69	0.54	0.35	0.49	0.171
78	M	-2.0	1.8	1.40	0.63	0.35	0.43	0.35	0.32	0.42	0.26	0.112

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