Multiple Color Matches to Estimate Human Color Vision Sensitivities

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Abstract. A color matching experiment was designed and carried out to estimate human observers' color matching functions (CMFs). 61 color-normal observers participated in the experiment. Their results were traced back to physiological factors using a mathematical vision model. The experiment time was 15 minutes, which is much faster than previous research aimed at determining color matching functions.

1 Introduction

Three active photoreceptors, sensitive to long, medium and short wavelengths (L-cone, M-cone, and S-cone) enable color vision for humans under photopic conditions. The light entering our eyes is integrated by these three sensors and color perception occurs. Thus, our color vision is characterized by a set of three sensitivity functions called color matching functions (CMFs). Knowing the CMFs of human observers is beneficial both for clinical purposes and color imaging workflow personalization [1]. CMFs are measured by color matching experiments. Color matching in general refers to the situation where there are two color fields: one fixed field and one adjustable field. One field is made of a fixed spectral power distribution (SPD). The other field is made of three primaries which can be adjusted by an observer so that the two fields appear the same. As human vision has three sensitivity functions, the match point can be uniquely determined by adjusting the three primaries. Measurement of CMFs is likely to be time-consuming and difficult for inexperienced observers because one needs to perform color matching on many reference spectra.

An alternative is to estimate CMFs utilizing a vision model, which has parameters to control the corresponding basis functions. To estimate CMFs, a given human observer would perform several color matches. The obtained results are used to estimate the vision model parameters and the observer's CMFs are reconstructed using the vision model with the estimated parameters as input. The number of required color matches depends on the number of parameters to be estimated, and is much less than that for measuring CMFs. In 1989, Fairchild developed the mathematical vision model with fifteen parameters which can be estimated from five color matches [2]. Later, Fairchild and North conducted a series of research to estimate CMFs [3] [4]. Similar attempts were made by vision researchers [5] [6].

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Recent studies have identified physiological factors that cause individual differences in CMFs [7] [8]. In 2013, Fairchild and Heckaman took advantage of the known individual differences in physiological factors, and constructed a mathematical vision model [9]. They generated 1000 sets of CMFs as a representative of color-normal observers through Monte Carlo simulation assuming a certain probability density function and a standard deviation for each physiological factor.

In this study, we apply the knowledge of physiological factors causing individual differences, present a method to estimate CMFs efficiently, and discuss the obtained results. The estimation method consists of a color matching experiment to capture human observers' CMFs characteristics and a vision model to estimate human observers' CMFs.

2 Experiment to Capture Human Observers' CMFs

2.1 Setup

We designed and conducted color matching experiments using a device originally developed by Sarkar and colleagues [10]. Schematic views of the device are shown in Figure 1. The device has two sets of LEDs, two corresponding integrating chambers, and presents a bipartite field to the observer. Software was developed that allows the observer to adjust the intensities of three LEDs to make a match with the reference field.

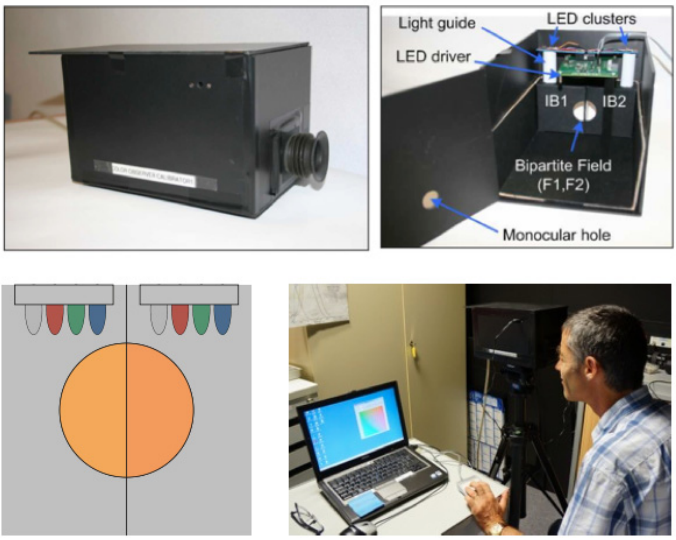

Fig. 1. Schematic views of color matching device

A maximum of four LEDs can be installed for each field of the device. The red, green, and blue LEDs on both fields were chosen based on our preliminary color

matching simulation. According to the simulation, these LEDs can magnify the individual differences in CMFs, and therefore, the detectability of the individual differences would increase. The fourth LED on both fields were chosen to be white LEDs. Again based on our simulation, the detectability of the individual differences in CMFs would increase if the reference color is achromatic. Figure 2 shows SPDs of LEDs used in this study. Note that these newly chosen LEDs are different from those originally chosen by Sarkar [11]. The newly chosen LEDs would produce larger observer variability than those chosen by Sarkar.

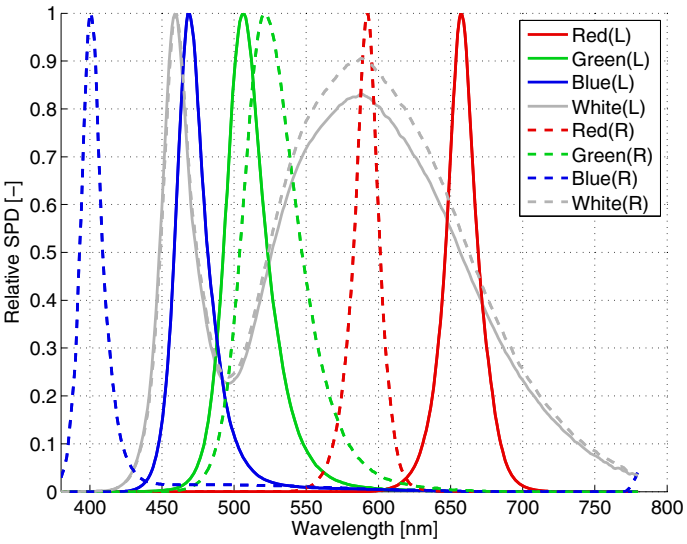

Fig. 2. SPDs of red, green, blue, and white LEDs on left and right fields. L and R denote left and right field in the device, respectively.

Each color match in this study was designed by selecting LEDs from the four LEDs in each field. Table 1 summarizes the LED combinations used for each color match. Color match 1 used R, G, and B LEDs on left field as matching primaries and white LED on right field as a reference SPD. Similarly, Color match 2 used R, G, and B LEDs on right field as matching primaries and white LED on left field as a reference SPD. Note that, although both color match 1 and 2 used R, G, B, and white LEDs, the spectral shapes of these LEDs on left field and right field are extremely different (as shown in Figure 2). Therefore, color match 1 and 2 could capture the observer variability in a different way. Color match 3, 4, and 5 used combinations of LEDs to produce reference SPDs. For color match 3, 4, and 5, the chromaticities of the reference SPDs were determined so that the reference SPDs should be as achromatic as possible. The luminances of all the five reference SPDs were about 25 $[cd/m^2]$. The device was both temporally and spatially stable enough. The temporal intensity changes of LEDs were less

than 1% 15 minutes after warm-up. The spatial intensity difference across the bipartite field was less than 6%.

CIELAB color space (lightness (L*), redness-greenness (a*), and yellowness-blueness (b*)) was used for a user-interface, which is more intuitive and more perceptually uniform than adjusting the raw intensities of the three primaries. Software was developed to convert the adjusted CIELAB values to the raw digital counts. Our preliminary color matching simulation revealed that the adjusted L* is relatively constant among all the color-normal observers. Therefore, we set L* constant for the experiment and the observer adjusted only a* and b* values to make a color match. Besides, two-dimensional color matching is advantageous because it is much easier than traditional three-dimensional color matching.

The number of necessary color matches is dependent on how many parameters have to be estimated. Since one color match outputs two variables and the vision model has four parameters (explained later), at least two color matches are needed. We chose to have five color matches in a whole experiment to increase the estimation accuracy. The output of this experiment are ten variables which would be uniquely determined by an observer's CMFs characteristics.

Table 1. LEDs used for each color match. Open circles represent the three matching primaries. Filled diamonds represent the LED(s) used to create the reference spectrum.

	Left				Right			
	R	G	B	W	R	G	B	W
Color Match Exp. 1	○	○	○					◆
Color Match Exp. 2				◆	○	○	○	
Color Match Exp. 3		○	○	○		◆	◆	
Color Match Exp. 4	◆	◆			○	○		○
Color Match Exp. 5	○	○	○		◆	◆	◆	

2.2 Procedure and Subjects

The subject was instructed to adjust one field of color to match the other field of color. Color adjustment was made through a user-interface equipped with four keys. Two keys increase or decrease a* (redness-greenness) and the other two keys control b* (yellowness-blueness). The subject sat in front of the device, fit one eye to the view port, observed the presented stimuli, and adjusted colors through the user-interface. For each subject, there are five color matches. Each color match was repeated three times. Before starting the experiment, a subject performed a trial match so that the subject becomes familiar with the user-interface. In total, there were 16 color matches (1 trial and 5 color matches with 3 repetitions).

61 color-normal subjects participated in the experiment. The subjects' ages varied from 20 to 53, and the average age was 39. 39 subjects were male while 22 subjects were female. 20 subjects were experienced observers and 41 subjects were inexperienced. 53 subjects were Europeans.

3 Vision Model to Estimate Human Observers' CMFs

The vision model used in this study is expressed as Equation (1)

$$T_\lambda = f(l, m, s_L, s_M) \tag{1}$$

, where T_λ is a set of CMFs corresponding to a given observer, l is a parameter to control lens pigment spectral transmittance, m is a parameter to control macular pigment spectral transmittance, and s_L and s_M are the λ_{max} shifts in L-cone and M-cone sensitivity curves, respectively. The vision model is essentially the same as the one used by Fairchild and Heckaman [9] except that the model corresponds to the field size of 8.5° instead of 2°. The model is also similar to CIE 2006 physiological observer function [12].

In this study, we assumed that CMFs of any color-normal observer could be found in the range of ± 3 standard deviations of each physiological factors. The standard deviations are based on Fairchild and Heckaman's work [9]. With respect to the lens parameter, it is dependent on the observer's age. Thus, the range of lens parameter was determined taking into account the participants' ages in this experiment (age 20 to 53) and a standard deviation of the parameter (± 20% of age). For each physiological factor, the interval and the number of steps were determined such that one step produces about 1 color difference in CIEDE2000 (ΔE_{00}), thus perceptually uniform. The range, interval, and the number of steps of each physiological factor used for vision model input are summarized in Table 2. A total of 115,101 sets of CMFs ($29 \times 21 \times 9 \times 21$) are generated by varying each physiological factor in the specified intervals.

The five color matches are computed for each set of the 115,101 CMFs. For a given human observer, his or her CMFs are determined as being the simulated CMFs set producing the closest color matches to his or her experimental results. The proximities between a human observer's results and the simulated color matches by CMFs were evaluated by color difference (ΔE_{00}).

4 Results and Discussion

The obtained color matching results are shown in Figure 3. Mean color difference from the mean (MCDM) [13] with CIEDE2000 (ΔE_{00}) was used to express inter- and intra- observer variability. As can be seen, inter-observer variability is well above the noise level (intra-observer variability). It makes the signal-to-noise ratio high, and it makes the estimation accurate.

As described in the *VisionModel* section, the CMFs were predicted and the corresponding physiological factors were estimated for each human observer. The prediction error was computed by color difference (ΔE_{00}) between the human observer results and the predictions averaged over five color matches for each human observer. The mean(±SD) prediction error was 1.7(±0.60). Given that the average noise level (intra-observer variability) is 1.6 ΔE_{00}, there would be the prediction error of 1.6 ΔE_{00} even if the observer's CMFs were perfectly estimated. In such context, the average prediction error of 1.7 is considered to be

Table 2. Range, interval, and the number of steps (from minimum to maximum) of each physiological factor used for vision model input. The ranges correspond to approximately ± 3 standard deviations of each factor.

	Min	Max	Interval (# of Steps)
Lens [Age]	10.0	80.0	2.5 (29)
Macula [%]	-100.0	100.0	10 (21)
Shift in L-cone [nm]	-4.8	4.8	1.2 (9)
Shift in M-cone [nm]	-7.5	7.5	0.75 (21)

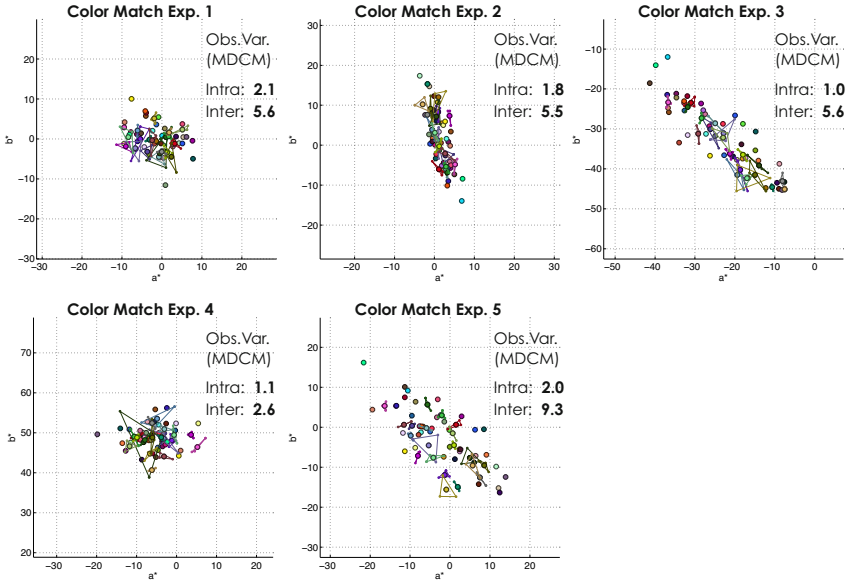

Fig. 3. Results from 61 human observers in five color matching experiments. Each filled circle is the average match point of three trials for each observer. The three trials are shown as small circles with connected lines for twenty observers. Inter- and intra-observer variability are shown for each color match.

quite satisfactory. The predictions could be further improved for the observers with errors larger than the noise level. Two possible reasons of the larger prediction errors would be: (1) ranges of physiological factors are not wide enough, and (2) four physiological factors are not sufficient to construct CMFs.

In Figure 4, the distributions of the estimated physiological factors are illustrated. As can be seen, the estimations violate the assumption of Fairchild and Heckaman model that the distributions of physiological factors are normal, and therefore, they are not physiologically plausible. This is especially true for the macula factor and the λ_{max} shift in L-cone factor where many observers hit the maximum limits. This implausibility could be explained by (1) the insufficient

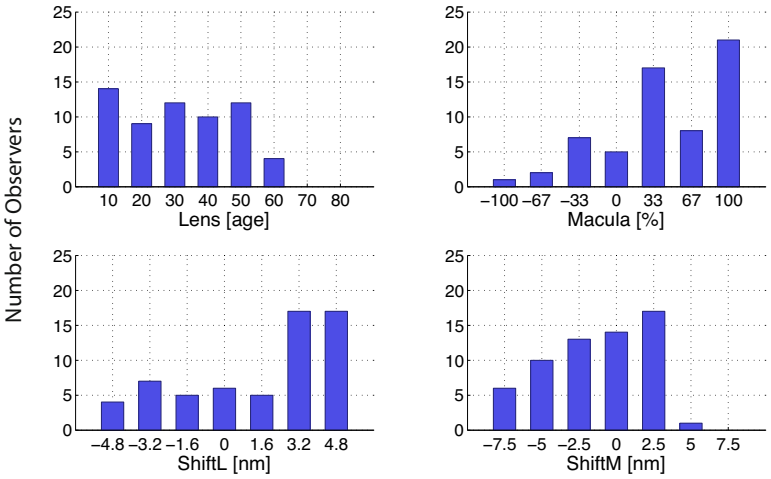

Fig. 4. The distribution of each estimated physiological factor. The interval corresponds to approximately 1 standard deviation.

ranges of physiological factors. It could also be explained by (2) the insufficient number of physiological factors; the four factors might have estimated the variability caused by more factors, and as a result, they might be deviated from the ground-truth. In fact, some researchers have shown individual variability in λ_{max} shift in S-cone [7] and the peak optical densities of L-, M-, and S-cones [8]. Figure 4 implies the need to revise the vision model with more physiological factors and to refine the ranges of physiological factors.

With respect to experiment time, according to Hu and Houser [14], it took about 3-6 hours to measure CMFs (18 color matches) with no repeated match. In North and Fairchild experiment [3], it took about 30 minutes for five color matches without repeated match to estimate CMFs. In this experiment, each human observer spent about 15 minutes for a whole experiment (one test trial, five color matches, and three repetitions). Such short experiment time was achieved mainly by introducing the two-dimensional color matching technique. Our experiment could be completed in as fast as 5 minutes if no repetition was needed.

5 Conclusion

The color matching experiment consisting of five color matches was designed and collected 61 color-normal observers' data. The experiment was aimed to estimate human observers' CMFs. The vision model developed by Fairchild and Heckaman was slightly modified and used to estimate human observers' CMFs. The obtained color matching results showed that the inter-observer variability was much larger than the intra-observer variability, which would make the estimation of CMFs accurate. The experiment took about 15 minutes, which is much

faster than previous research. The predictions were satisfactory on average. Further improvements for the model predictions and the physiological plausibility of estimated factors could be made by revising the vision model, adding more physiological factors and refining the range of physiological factors.

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