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Measurement of Confusion Color Pairs for Dichromats in order to Use Applications Supporting Color Vision Deficiency

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Abstract*—Recently, various applications of mobile devices supporting color vision deficiency are released. However, applications supporting color vision deficiency may not work as designed performance. Color calibration and personalization are needed when the user uses such an application, because a color representation performance of devices is distinct from each other, and users may also have individual differences in characteristics of color vision. Thus, confusion color pairs will change slightly. Conversely, it will be a clue for color calibration or personalization in oder to reduce changes. Here, we propose methods determining confusion color pairs by a simple operation to achieve it. We estimate color pairs by the procedure as a bisection method in order to determine them. A user is presented with the three visual stimuli (a reference and two targets). The user selects one of test targets whose color is perceived more similar to reference's color. We focused on how to select visual stimuli's colors. We propose two methods to select ones, which are represented the coordinates on $u'v'$-chromaticity diagram. One method uses colors on a circumference whose center corresponds to the white point. Another method uses colors on parallel lines to the line passing through primary colors (green and blue). We obtained results that it shows comparable performance determining color pairs to previous studies. Results of lines' method show that performance is better than the circumference method. And, its measurement time is reduced.

I. Introduction

Recently, various applications for smart phones or tablet devices supporting color vision deficiency are released [1]. For examples, screening test applications are often shown. Based ideas of such applications have been proposed more than 25 years ago. Tests of Panel D-15, color matching, MacAdam's ellipse measurement on a CRT controlled by a PC had implemented [2]. The Fransworth Munsell 100-hue test using computer graphics hardware (digitally controlled color television monitor) [3] and a modified version of the Fransworth D-15 test on a video display had been implemented. The test using OKN (optokinetic nystagmus) by a series of image sequence on a computer-controlled TV display was proposed [4] Screening test with a standard CRT display which is used in a clinic has been proposed [5]. A web-based remote screening test with non-calibrated monitors has been also proposed [6]. It makes the point that individual color properties of devices are not negligible for such applications. It solves the problem by presenting lots of various visual targets whose colors are changed.

Merits of recent applications are interactive operations and providing the information in a scene. Some applications acquire images through a camera, and display the color categories (e.g., red, green, gray and so on) or extracted similar color regions of the focused (clicked or bounding) area in the image. In this situation, the color properties of the camera or the screen of the device may cause incorrect matches between the acquired and/or displayed data and image processing algorithm's data. In another application, after the acquiring processing an image, similar color regions (e.g., greenish areas) are extracted from the image by pointing operation such as a click or a bounding area by the interaction of a user. The color properties of camera, screens and user effect with the performance of an application program in this situation.

Some applications find the confused color regions in the acquired image, and convert to the colors which are easy to discriminate which are based on the model of the dichromats' color appearance (e.g., Brettel *et al.*'s model [7]). It calculates the confusion loci under the assumption of perfect deficient of one of the L, M, S cones. In this case, incorrect matches of color properties cause effect more strongly. The difference in the color representation performance of devices affects a finding confused color application and a color-convert one. Especially, the color-convert application is highly affected by the color characteristics of a user. As a method of color transformation, e.g., methods based on information of original image[8] or genetic algorithms[9] is proposed, and subjective assessments of enhanced images [10][11] are reported.

A color representation performance of devices is distinct from each other, and users may also have distinct differences in characteristics of color vision. Therefore, applications supporting color vision deficiency will not work as designed performance, because there are factors that the represented color on the device is not matching the calculated color in the application's algorithm and/or user's percept is not corresponding to the characteristics of color appearance model. It is proper that applications' algorithm colors and percept are matched.

Fig. 1 shows that some devices (a laptop PC and a smart phone) and sRGB color gamuts are presented at the coordinate on the $u'v'$-chromaticity diagram. The vertices of the triangle

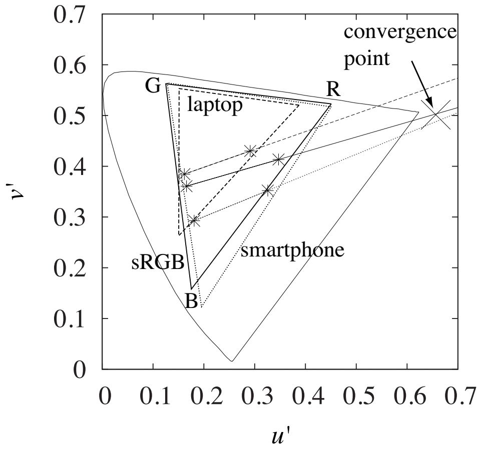


Fig. 1. Outputs by the same pair of RGB signals with the individual profile of devices or the sRGB profile. The vertices of the triangle correspond to primary colors (right: R, top left: G, bottom: B). Only the case of the sRGB profile, the line corresponds to a confusion locus passing through a convergence point which is shown by a mark of 'X'.

correspond to primary colors (right: R, top left: G, bottom: B). Two same-value RGB signals are indicated by marks of '$\ast$' in the gamuts, respectively. Only the case of sRGB, color pairs of two RGB signals are located on the confusion locus passing through the convergence point which is based on the theory of cones' properties, and these colors are a confused color pair. However, colors of these two RGB signals can be discriminated when they are displayed on these devices. Standard color formats or profiles of devices are existing and are able to be set. However, we may set it to the favored pre-set color profile, use it under the various ambient light, or wear the glasses with cutoff a specified wavelength light. Furthermore, the individual characteristics of users may cause a shift of the convergence point. Then, it affects processing on a color system in applications. Therefore, it is desirable to measure color characteristics of a user's appearance easily when he/she use applications.

Here, we propose the method of determining the confusion color pairs that correspond to confusion loci when we measure under the conditions of simple operation. Since we suppose applications for smart phones or tablet devices, so complicated operations are not proper to implement for them. It is useful to estimate the confusion color pairs that we can match/correct signals (colors) in the algorithm to output signals in devices. Errors of signals are caused by the factors, that is, a property of the device, visual environment (ambient light etc.), and characteristics of a user. Here, we treat of the last ones.

The precise measurement of the confusion color on a PC monitor [12] was reported. In the paper, discrimination ellipses are estimated by the visual target which is displayed a form of C like a Landolt ring. It is composed with small color patches as a foreground, and looks like a pseudoisochromatic plates. The foreground colors of the patches are painted with the desired color to be measured. As a required time for measurements, it takes about 4 minutes for the determination of confusion-type. And, it takes about 20 minutes at the maximum for the determination of major axis of discrimination eclipse which corresponds to the confusion locus.

We aim to estimate the confusion color pairs under the conditions of measuring by the uncomplicated operation and within a reasonable time as applications.

The rest of this paper is organized as follows. Section 2 describes two proposed procedures for measuring the confusion color pairs. Experimental results for one dichromat and discussion are in section 3. Finally, section 4 concludes the paper.

II. METHOD

We used a forced-choice method for the task that the similar color's panel to reference panel is selected from two tests (target) color panels on the screen of a monitor. Here, we name a visual target to a panel. The color of non-selection target panel was updated as according by a bisection method. It may converge faster than a method of limits.

We showed three color panels on the LCD monitor as a visual target as shown in Fig. 2. The center is referenced target and the both ends are targets. The background was filled with black pixels.

A subject selected the target panel whose color was perceived nearer to the color of the reference panel. We updated the non-selected panel's color that becomes more similar color of the selected one by according the bisection method for two targets. That is, averaged color is presented. After a selection, a screen of the monitor was refreshed to black color about 1 second, and updated visual stimuli whose target panels' locations are replaced randomly were displayed. The subject repeated this selection procedure. When the subject couldn't perceive the color difference between two target panels, the procedure was terminated and recorded the color of the middle point with two targets on $u'v'$-chromaticity diagram. In the case that a subject perceives that both target panels are not similar to the color of reference, the trial is cancelled and is retried with new initial random color sets of visual stimuli. We did trials until 10 confusion color pairs are recorded as one session.

Here, we propose two methods as a criterion of a color property in displaying panel's color. We utilized the $u'v'$-chromaticity diagram which is designed based on perceptual color difference as a color space. Roughly speaking, MacAdam's ellipses distribute to similar size in this color system.

A. *Selection method from colors on a circumference*

In this method, we chose stimuli (two targets and one reference) from colors that hold constant distance from the

Fig. 2. Example of visual stimuli (left: target (greenish color), center: reference (reddish color), right: target (bluish color))

white point on $u'v'$-chromaticity diagram. That is, the colors are selected on the circle whose origin is a white point (see Fig. 3). We set a radius to the maximum value within the monitor's color gamut.

The colors of visual targets are selected as followings.

1) The reference's color is determined as the color on the circumference at the angle of θ_r, randomly.
2) As one target color, the color on the circumference at the angle of θ_1 far from the reference by at least $\frac{\pi}{2}$ ($\theta_1 \geq \theta_r + \frac{\pi}{2}$ or $\theta_1 \leq \theta_r - \frac{\pi}{2}$) is selected.
3) As another target color, the color on the circumference at angle of θ_2 that space from to the target by $\frac{\pi}{3}$ and is far from the reference ($\theta_2 = \theta_1 + \frac{\pi}{3}$ or $\theta_2 = \theta_1 - \frac{\pi}{3}$)is selected.

In the process of updating the color, the color is calculated as the intersection of an angle bisector ($\frac{\theta_1+\theta_2}{2}$) of two targets and the circumference.

Since the reference was possible to be set any positions on a circumference, we proposed this method as the merit that it was independent on the type of dichromat user.

B. Selection method from colors on two parallel lines

Another method is that stimuli are selected from two lines parallel to line passing through primary colors (Green and Blue) which we abbreviate to GB-line (see Fig. 4).

Table 1 shows the coordinates of convergence points (three types) of confusion loci [13]. The values of u', v' were calculated from the x, y values of convergence points in [13].

Since the convergence point of tritan lies at around the coordinates (0.28, 0.0), we can't obtain confusion loci that pass through the coordinates of color pairs on these two lines. As a result, we are limited to measuring characteristics of the user who is a protanope or a deutanope in this setting. However, we proposed this method as the merit point that we can take a large color difference of the visual target. And it will contribute to the reduction of measurement errors. If we select the two lines as e.g., $v' = 0.5$ and $v' = 0.4$, we can measure confusion color pairs for tritanope.

Here, we determined two lines as follows. One line (green/blue side) was selected as the location that the ratio of the distance of the GB-line to one of the white point is 1 to 9. Another line (red side) was selected as the location by a factor of three of distance between the GB-line and white point. The color on each line was assigned for a reference or targets.

Next, we utilized the coordinates of convergence points of these types in order to determine the color of reference and colors of targets.

The colors of the visual target are selected as followings.

1) One of two convergence points is determined, randomly.
2) The reference's color in the one of two parallel lines is determined, randomly.
3) Based on this color, the confusion line which passes through the coordinates of reference's color and the selected convergence point is calculated.
4) The intersection point of confusion line and targets' line is calculated.
5) Two targets' colors are selected in the colors of the coordinates which are spaced by 0.02 ($u'v'$ unit) from the intersection point.

In color-update process, it is calculated as the color of middle point between two target colors.

TABLE I. CONVERGENCE POINTS OF CONFUSION LINES

	u'	v'	x	y
protan	0.6564	0.5015	0.7465	0.2535
deutan	-1.2174	0.7826	1.4000	-0.4000
tritan	0.2810	0.0000	0.1848	0.0000

III. EXPERIMENT

A. Apparatus and Procedure

We focused on the measuring method on personal color characteristics on users. Therefore, we experimented with a calibrated monitor under no ambient lights.

We set up an LCD monitor in a darkroom. No light was in the darkroom. Specification of the monitor (EIZO ColorEdge CG210) is as follows. The size of the display area is 432 mm ×324 mm (1,600 × 1,200 pixels). The dot pitch is 0.27 mm × 0.27 mm. Each primary color (Red/Green/Blue) can represent in 256 (8 bits) gradation steps, which are calibrated from hardware specs (10 bits) based on the hardware calibration. We calibrated that the gamma value of each primary color was set at 2.2, the color temperature was set at 6,500 K, and luminance level was set at 100 cd/m^2.

A subject observed the monitor with chin-rest. The distance between the subject and the monitor is kept to 0.6 m. In this setting, the size of visual stimuli is 8.6 arcdeg for each plate with side 9.0 cm.

The monitor was set at sRGB mode and was measured the color gamut by a luminance and color meter (Konica Minolta CS-200). The measurement results are shown in Table 2.

We derived the following equation for this monitor from these measurement results and the transformation equation of Lv_i to Y_i:

$$Y_i = \frac{Lv._i - Lv._{Black}}{Lv._{White} - Lv._{Black}} \times 100. \quad (1)$$

Here, assigning Y_i= 20, $Lv._{White}$= 105.13, and $Lv._{Black}$= 0.17 to (1), then we obtain the value of luminance level at $Lv._i$= 21.2 cd/m^2.

TABLE II. COLOR PROPERTIES OF LCD MONITOR (CG210)

color	8 bit RGB signals	$Lv.$ cd/m^2	x	y
white	(255,255,255)	105.13	0.3093	0.3268
black	(0,0,0)	0.17	0.2378	0.2392
red	(255,0,0)	22.78	0.6421	0.3232
green	(0,255,0)	76.36	0.2917	0.6150
blue	(0,0,255)	7.49	0.1476	0.0567

Next, we derived the Linear RGB value from the following equation.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 42.80 & 34.43 & 18.15 \\ 21.54 & 72.59 & 6.97 \\ 2.31 & 11.01 & 97.87 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix}, \quad (2)$$

where XYZ and RGB are, respectively, CIE XYZ and corrected Linear RGB in the range from 0 to 1. And, X and Z hold the following equation.

$$\begin{pmatrix} X \\ Z \end{pmatrix} = \begin{pmatrix} Y\frac{x}{y} \\ Y\frac{(1-x-y)}{y} \end{pmatrix}. \quad (3)$$

We derived 3×3 coefficient matrix in (2) by assigning Y (=Y_i which is calculated by substituting the values of Lv in Table 2 for (1)) and x, y for each primitive color in Table 2 to (3).

In order to calculate the RGB signal to monitor, we fix the chromaticity (x, y and Y (as described above, we set at 20)) in CIE XYZ, then X and Z are calculated by (3). Next, we assign them to (2) , then we obtain linear RGB value. Finally, we transform linear RGB to RGB value through the operation of gamma correction and digitalize to fit them within the dynamic range of 8 bits.

B. Results and Discussion

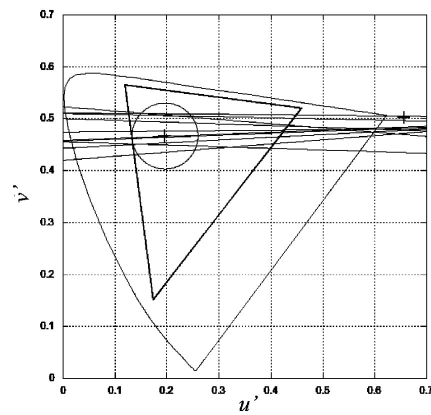
One subject with consensus was participating in this experiment.

Results of determing confusion color pairs and corresponding loci which are lines passing through their pairs are shown in Figs. 3 and 4. These show results which are based on the method of colors on a circumference and two parallel lines, respectively. The results are plotted on $u'v'$-chromaticity diagrams. The gamut which perceives color by the human is presented as a horseshoe-shaped region that is surrounded by a curve and a line. The triangle area (right: Red, top left: Green, bottom: Blue) shows the color gamut of the LCD monitor which we used in this experiment. The mark of '+' within the triangle region means the coordinates of the white point. A circumference and lines on which the colors of visual stimuli are selected are shown in figures.

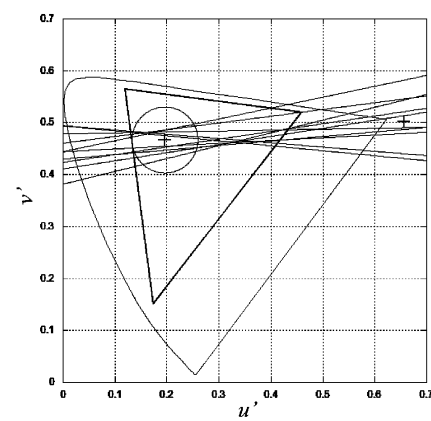
The mark of '+' outside of the gamut of human represents the convergence point of confusion lines for protan's appearance model. The convergence point (u', v') = (-1.2174, 0.7826) of deutan's appearance model lies as far left side of these figures. After estimating the confusion color pair, we draw the line passing through two colors. If measurement results obey the dichromats' color appearance model, lines should pass through one of convergence points. However, such lines have not always been observed. Although we don't show plots near at the convergence point (u', v') = (-1.2174, 0.7826) of deutan, we confirmed that the lines didn't converge there.

Therefore, we calculated the coordinates which minimized the sum of the distance from each confusion line as a following equation:

$$\mathbf{x}_{cp} = \underset{\mathbf{x}}{\operatorname{argmin}} \sum_{i}^{n} \frac{|\mathbf{w}_i^T \mathbf{x} + c_i|}{\|\mathbf{w}_i\|}, \quad (4)$$



(a) 1st session



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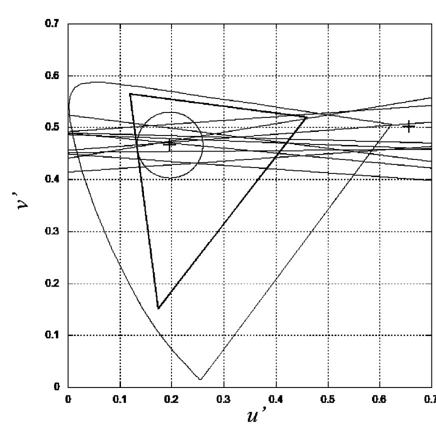
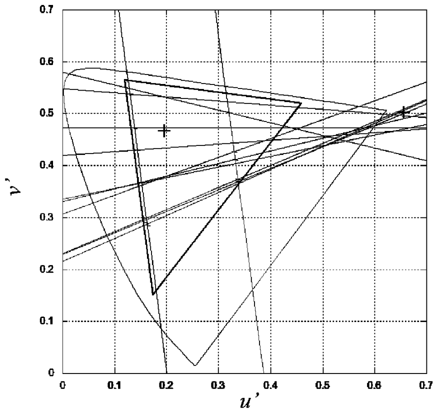


(c) 3rd session

Fig. 3. Results on the method of colors on a circumference

where $\mathbf{w}_i = (a_i, b_i)^T, \mathbf{x} = (u', v')^T$, a_i, b_i ,c_i are the parameters of the equation, when we denote the ith confusion locus as the form as $a_i u' + b_i v' + c_i = 0$. n is the number of measured confusion locus (here, n=10).

Next, we calculated the standard deviations $\boldsymbol{\sigma} = (\sigma_{u'}, \sigma_{v'})^T$ as a measure of fluctuations of convergence for each coordinate.



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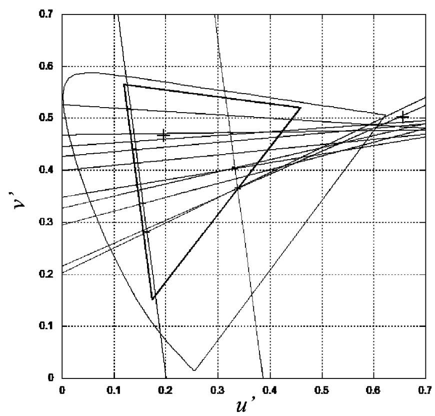

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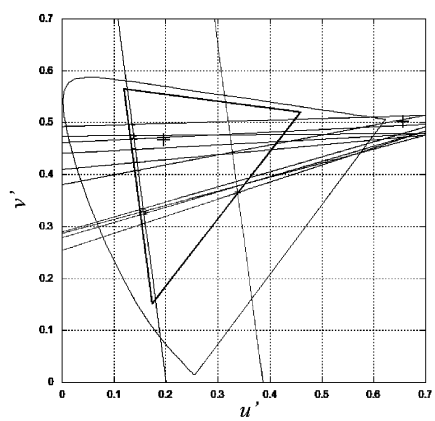


(c) 3rd session

Fig. 4. Results on the method of colors on two parallel lines

$$\sigma_{u'} = \sqrt{\frac{1}{n}\sum_{i}^{n}\left(u'_i - u'_{cp}\right)^2} \tag{5}$$

$$\sigma_{v'} = \sqrt{\frac{1}{n}\sum_{i}^{n}\left(v'_i - v'_{cp}\right)^2}, \tag{6}$$

where we denote a foot of a perpendicular line of ith confusion line through $\mathbf{x}_{cp} = (u'_{cp}, v'_{cp})^T$ which is calculated from (4) as $\mathbf{x}_i = (u'_i, v'_i)^T$.

The results show in Figs. 5 and 6, Table 3.

In the Figs. 5 and 6, we show the $\mathbf{x}_{cp}$ and the interval of $\sigma_{u'}, \sigma_{v'}$ for horizontal and vertical axes, respectively.

As we can see in Table 3, $\sigma_{v'}$ is four or five times greater than $\sigma_{u'}$, at least. Since the lines are near to the parallels to the horizontal axis, then this is reasonable results. However, it seems that the differences between sessions are far larger than these intervals.

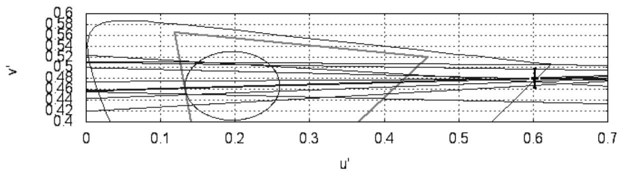
From these results, we conjecture that the calculated convergence point is not corresponding to one of protan or deutan exactly. However, they are distributed at the near coordinates of the convergence point for protan in the Fig.3 (a) and all of Fig 4. At least, most of the confusion lines don't direct toward the coordinates (-1.217, 0.783) of deutan's point in Figs. 3 and 4.

To compare with two methods, the method base on the colors on two lines outperforms the method based on colors on a circumference as a whole. However, when we consider the error for each session, there is a case that circumference's method has comparable performance to the lines' method. It corresponds to the results in the 1st session of circumference's method and the 3rd session of lines' one. The values of v' are almost same for any session of both methods. As a reason that large error of u' occurs in the case of circumference, we conjecture that the coordinates of presenting colors are closer than the ones of colors on two lines. When we draw the line passing through two points with some degree of errors whose magnitude is almost same, a fluctuation of the line tends smaller as the two points are farther. Therefore, although the circumference's method has merits that it holds a constant color difference and it doesn't depend on types of color vision deficiency, there is a demerit that the estimation error of the convergence point is large in some cases. To realize the estimation of the location of the convergence point more precisely, for example, we will need to add the weighted process which reflects the variation of the distance between color pairs.

If we calculate the convergence point of the only lines that are passing through the model's convergence point, we will obtain more precise coordinate. We calculated with (4). It assigned the equivalent weight for all lines. Outliers may affect the results.

We can see that there is the shift between the estimated convergence point and the point of dichromats' appearance model, even if we consider such errors. It may present that it reflects personal color characteristics of the subject. If it is true, it is effective that the estimated coordinates are stored and we utilize to replace the model's convergence point with it in order to realize personalization of applications supporting color vision deficiency.

Next, we will discuss the measurement time and the number of trial cancellations in Tables 4 and 5. From the Table 4, we can see that line's method outperforms circumference's one in this criterion. The required time for the measurement



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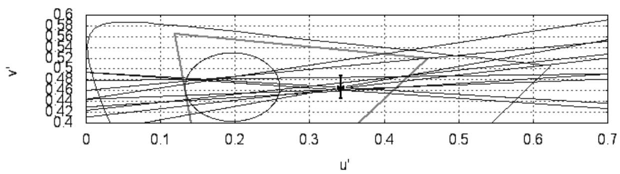

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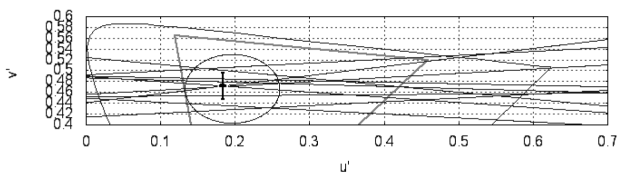

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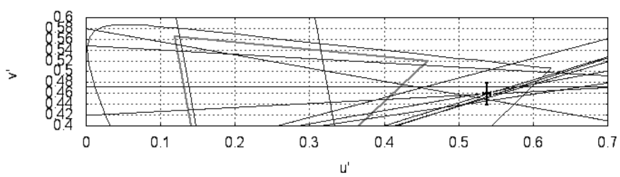
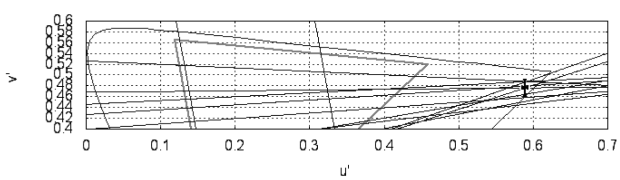
Fig. 5. Estimated convergence point of the method of colors on a circumference



(a) 1st session



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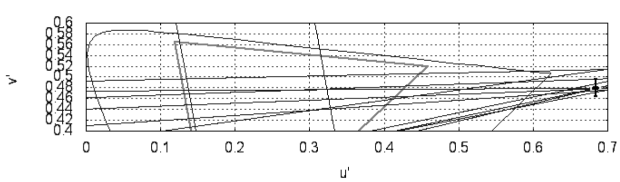

(c) 3rd session

Fig. 6. Estimated convergence point of the method of colors on two parallel lines

of the lines' method is about 64% of circumference's one. For this reason, we can see from the result that the number of the lines' cancels is about 26% of circumference's ones in Table 5.

Furthermore, we examine the detail of cancels for lines' method. It is given in Table 6. The column with heading

TABLE III. ESTIMATION VALUE OF CONVERGENCE POINT

	colors on a circumference			
	u'	$\sigma_{u'}$	v'	$\sigma_{v'}$
1st session	0.602	(0.001)	0.480	(0.018)
2nd session	0.342	(0.004)	0.466	(0.021)
3rd session	0.184	(0.002)	0.472	(0.024)
average	0.376	-	0.473	-
protan	0.656	-	0.502	-
deutan	-1.217	-	0.783	-

	colors on two parallel lines			
	u'	$\sigma_{u'}$	v'	$\sigma_{v'}$
1st session	0.538	(0.005)	0.459	(0.020)
2nd session	0.590	(0.003)	0.476	(0.014)
3rd session	0.684	(0.002)	0.479	(0.016)
average	0.604	-	0.471	-
protan	0.656	-	0.502	-
deutan	-1.217	-	0.783	-

TABLE IV. REQUIRED TIME OF MEASURING

	colors on a circumference	colors on lines
1st session	311	156
2nd session	269	174
3rd session	175	158
average	252 (sec)	162 (sec)

TABLE V. THE NUMBER OF CANCELS.

	colors on a circumference	colors on lines
1st	36	7
2nd	41	8
3rd	15	9
average	31	8

TABLE VI. THE CANCELLATION RATES FOR LINES' METHOD

	# of cancellations	cancellation rates		valid trials	
		protan	deutan	protan	deutan
1st	7	4/13	3/4	9	1
2nd	8	3/13	5/5	10	0
3rd	9	1/11	8/8	10	0

"cancellation rates" shows the number of cancels/presenting. For example, the cell which is written "4/13" in "protan" means that protan point is chosen in 13 trials as an initial convergence point and the cancels occurred in 4 trials. As a result, 9 trials are valid as the last column in the table, and it is determined confusion color pairs. From this result, we can conjecture that the subject is a protanope. We can utilize such a canceling tendency of trials to estimate the type of color vision deficiency. Then, we can realize that measuring time is shortened by changing an initial presenting colors' pair based on the type of color vision deficiency.

From the location of the convergence point and the cancellation results, we conjectured the type of dichromats of this user as a protanope. It took about 3 minutes as a measurement time for the determination of confusion-type in the case of lines' method. In the measurement of Regan *et al.* [12], it took about 4 minutes. At this point, the proposed method has a comparable performance of the previous study.

IV. CONCLUSION

We proposed the method of determining the confusion color pairs which are user's characteristics of color vision under the condition of a simple operation. We adopted the method of selecting one panel from two test color panels on the screen of a monitor, which is perceived more similar to the reference color panel. We proposed two methods determining the colors of test color panels. One is the method that we choose stimuli from colors that hold constant color distance from the white point on $u'v'$-chromaticity diagram. Another is the method that stimuli are chosen from two lines which parallel to the line passing through primary colors (green and blue). From experimental results, we confirmed both methods were able to estimate the type of color vision deficiency. To compare two methods, we obtained results that performance of lines' method was better and measurement time was shortened.

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