https://doi.org/10.2352/issn.2169-2629.2021.29.148

Effect of digitally generated colored filters on Farnsworth-Munsell 100 hue test by red-green color vision-deficient observers

Shunnma Saito, Graduate School of Engineering, Kagawa University, Takamatsu, Kagawa, Japan
Keiko Sato, Faculty of Engineering and Design, Kagawa University, Takamatsu, Kagawa, Japan

Abstract

In this study, the effects of four different digitally generated colored filters on the Farnsworth-Munsell 100 hue test (100-hue test) are analyzed by red-green color-vision deficient (CVD) observers. We digitally simulate the colored filters based on the spectral transmittance of four colored filters, which have been used previously. Five red-green CVD observers are subjected to the 100-hue test on a monitor under nine filter conditions, which comprise one condition without filter and eight conditions with filters. The results suggest that a colored filter that transmits long wavelengths and absorbs medium wavelengths may improve the color discrimination performance of protans and deutans.

Introduction

Congenital color vision deficiency refers to the lack of one among three cone cells in the retina: long-wavelength (L), middle-wavelength (M), and short-wavelength (S) cones. Color vision deficiencies can be classified into three primary categories: protan, deutan, and tritan. The protan and deutan types are collectively referred to as red-green color-vision deficient (CVD). The protan type arises owing to the lack of the normal L-pigment gene (protanopes) or to the presence of the L-M hybrid gene (protanomalous). The deutan type is associated with either the deletion of the normal M-pigment gene (deteranopes) or the presence of the M-L hybrid gene (deuteranomlous). The dicromatic form is more severe than the trichromatic form; the anomalous trichromatic form varies from weak to severe, and the severity range of the anomaly is wide [1]. As red-green CVD individuals exhibit functional abnormalities in the normal L- or M-cone visual pigment, they occasionally confuse such color pairs as they do not possess the red-green opponent mechanism. A previous study reported that these individuals experienced inconvenience in performing daily activities, e.g., color discrimination of railroad maps, as well as restrictions in their choice of occupation, e.g., not being able to work as a pilot [2][3].

Hence, numerous studies pertaining to task assistance for CVD observers have been conducted. In particular, wearable colored filters have been investigated. The concept of a colored filter was proposed by Seebeck in 1837 [4], followed by the design of glasses based on this concept to aid color discrimination among red-green CVD observers [5]. Subsequently, it has been applied to commercial eyeglasses and contact lenses. For example, the X-Chrom contact lens developed by Zeltzer [6] is a red filter that transmits long-wavelength light (but also transmits short-wavelength light). Other examples include ChromaGen contact lenses (ChromaGen Ltd., Chester, UK) [7], Atto565 contact lenses [8], EnChroma eyeglasses (Enchroma, Inc., Berkeley, USA), VINO eyeglasses (VINO Optics), ColorMax (ColorMax Technologies Inc., Tustin, CA, USA), Coloryte (Coloryte Hungary Rt, Szentendre, Hungary), and ColorView (ColorView Inc. Fremont, CA, USA).

The effects of pseudoisochromatic plates and color arrangement tests from these colored filters have been evaluated via color vision tests. Hovis confirmed the improvement in the performance of red-green CVD observers on the Farnsworth-Munsell D-15 test (D-15 test) by performing filtering using unique colored filters [9]. Furthermore, Gómez-Robledo et al., who analyzed the effect of EnChroma glasses, and Martínez-Domingo et al., who analyzed the effect of VINO glasses, conducted the Ishihara test, the 100-hue test, and a color-naming test for CVD observers [10][11].

Sato et al. investigated the effects of digitally simulated colored filters and identified the mechanism that contributed to changes in red-green CVD observer performance on the D-15 test behind a colored filter [12]. Specifically, they simulated a red filter on a digital monitor based on a spectral transmittance similar to that of the X-Chrom lens, used by Dianonu et al. [13]. The effect of the colored filter on the monitor was verified via the D-15 test. To investigate the red-filter effect, we confirmed whether the red filter improved the performance of red-green CVD observers in the D-15 arrangement test. Two main problems are reflected in the study of Sato et al. [12]. First, the red filter simulated in their study improved the performance of deuteranopes but deteriorated the performance of protanopes. Second, the D-15 test may not have sufficiently evaluated the color discrimination performance of CVD observers. Hence, this study was performed to identify colored filters that can improve the color discrimination performance of protan observers. We simulated filters on a monitor based on the spectral transmittance of three commercial colored filters, in addition to the red filter used by Sato et al. [12]. To evaluate the performance of color discrimination, we performed the 100-hue test, which is a color vision test that can evaluate color discrimination performance more comprehensively than the D-15 test, and simulated it on a monitor. In the experiment, five red-green CVD observers performed the 100-hue test without filters and with four types of filters. Based on the results, we analyzed the effects of colored filters simulated on the digital monitor on the color discrimination of red-green CVD observers as well as the characteristics of colored filters.

Simulation of colored filter

We simulated the four colored filters on the monitor based on commercial filters ChromaGen 'P' (P), ChromaGen 'Y' (Y), ColorMAX 'D5' (D), and a red-tinted filter similar to X-Chrom (X), similar to Moreland's study [14]. Subsequently, the XYZ tristimulus values were calculated, and then converted to linear RGB values using Equation (1). The spectral distribution of the monitor was measured in 0.5 nm steps with a spectrometer (StelaNet, BLACK-COMET), and the transformation from XYZ to RGB was tailor-made specifically for the monitor.

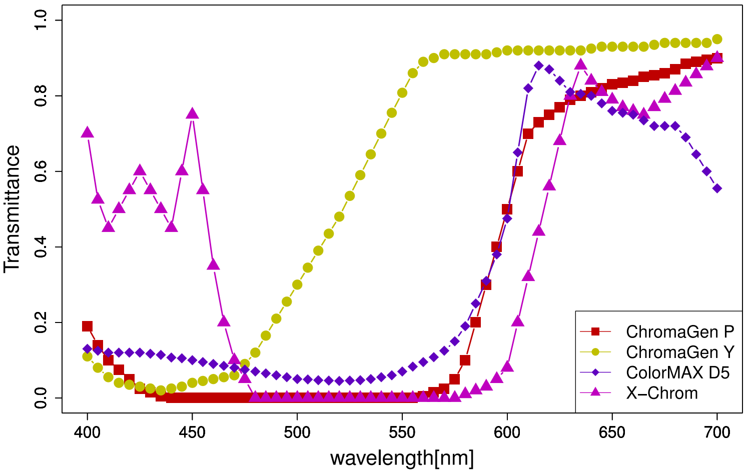

Figure 1. *Spectral transmittance of colored filter simulated digitally in current study*

Table 1. XYZ tristimulus values of four colored filter

Filter	X	Y	Z
ChromaGen P	30.8	15.9	1.1
ChromaGen Y	69.8	71.5	7.1
ColorMAX D5	26.4	9.9	42.8
X-Chrom	36.2	21.8	10.3

$$\begin{bmatrix} r \\ g \\ b \end{bmatrix} = \begin{bmatrix} 2.0489 & -0.579 & -0.358 \\ -0.9769 & 1.9224 & 0.0444 \\ 0.0169 & -0.094 & 0.9833 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{1}$$

Finally, the RGB values were converted to gamma-corrected monitor RGB values. Table 1 shows the XYZ tristimulus values of the four simulated colored filters.

Experiment

Subjects

Five red-green CVD individuals participated in the experiment. Written informed consent was obtained from all participants according to an experimental protocol approved by the Ethics Committee of Kagawa University (30-002). The deficiency type and severity of the participants were determined using an anomaloscope (NEITZ OT-II, Neitz Instruments Co. Ltd.), two protanopes (P1 and P2), two deuteranopes (D1 and D2), and one deuteranomalous trichromat (D3).

Stimuli

Color stimuli were selected based on the 85 caps of the 100-hue test. The 100-hue test is a color vision test in which 85 colored caps must be arranged in the correct hue order. This test comprises four boxes: Box 1 in the range of red to green (cap no. 85 and nos. 1 to 23), Box 2 in the range of green to blue (nos. 21 to 44), Box 3 in the range of blue to purple (nos. 43 to 65), and Box 4 in the range of purple to red (nos. 64 to 85 and no. 1). The 85 color stimuli were simulated on the monitor based on the u^*v^* values of the 100-hue test referring to [16]. We show the u^*v^* reference values and the XYZ tristimulus measured values, which were measured with a colorimeter (EIZO EX2, EIZO Corporation), in Appendix. The background was set to neutral gray (X = 18.3; Y = 19.3; Z = 21.0) based on the Munsell value, N5.

For the filter effects of the color stimuli, we combined the original color stimuli with the simulated filter using alpha compositing. Alpha compositing is the process of overlaying a foreground image with transparency over a background image. Equation (2) expresses the blending of the original stimuli and the simulated filter.

$$\begin{aligned} R' &= (1-\alpha)R + \alpha R_{\mathrm{F}}, \\ G' &= (1-\alpha)G + \alpha G_{\mathrm{F}}, \\ B' &= (1-\alpha)B + \alpha B_{\mathrm{F}}. \end{aligned} \tag{2}$$

where (R, G, B) is the original stimuli, $(R_{\mathrm{F}}, G_{\mathrm{F}}, B_{\mathrm{F}})$ is the simulated filter, and (R', G', B') expresses the blending stimuli after α compositing. Alpha is generally used as a parameter that represents opacity. If the opacity level of the filter is 0, then the filter is fully transparent and hence invisible (only the original image is visible). By contrast, an opacity level of 1 yields a fully opaque image. Sato et al. designed the three alpha conditions for the opacity levels, i.e., $\alpha = 0.1$, 0.3 and 0.5, however, for the protanope subjects, color loss tended to increase with opacity[12]. Thus in our experiment the two alpha conditions for the opacity levels, i.e.,$\alpha = 0.1$, 0.3, were used except for 0.5.

Procedure and apparatus

Each participant performed the 100-hue test, which comprised four boxes, by arranging the colored caps into a hue sequence. The order of the color caps of Box 1 was displayed randomly. After the participant completed the arrangement, the next box was presented. A 1000 ms fixation time was presented between the trials. Each participant performed the 100 hue-test under nine conditions: without filter and with filter (four filter types and two transparency conditions). The order of the conditions was randomized. Each condition was conducted twice. An overview of the experimental flow is presented in Figure 3. The experiment was conducted using a calibrated monitor (ColorEdge CX270, EIZO Corporation) under a D65 light source in a dark room. The participant's head was fixed with a chin rest, and the viewing distance was 55 cm. The program was controlled using Visual C#.

Result

To evaluate whether the simulated colored filters improved the performance of the arranged colored caps in the 100-hue test, we quantified the discrimination performance using the scoring

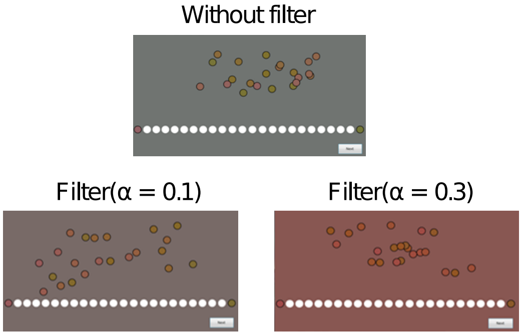

Figure 2. *Examples of experimental screen (top: without filter; bottom left: with filter of opacity level 0.1; bottom right: with filter of opacity level 0.3)*

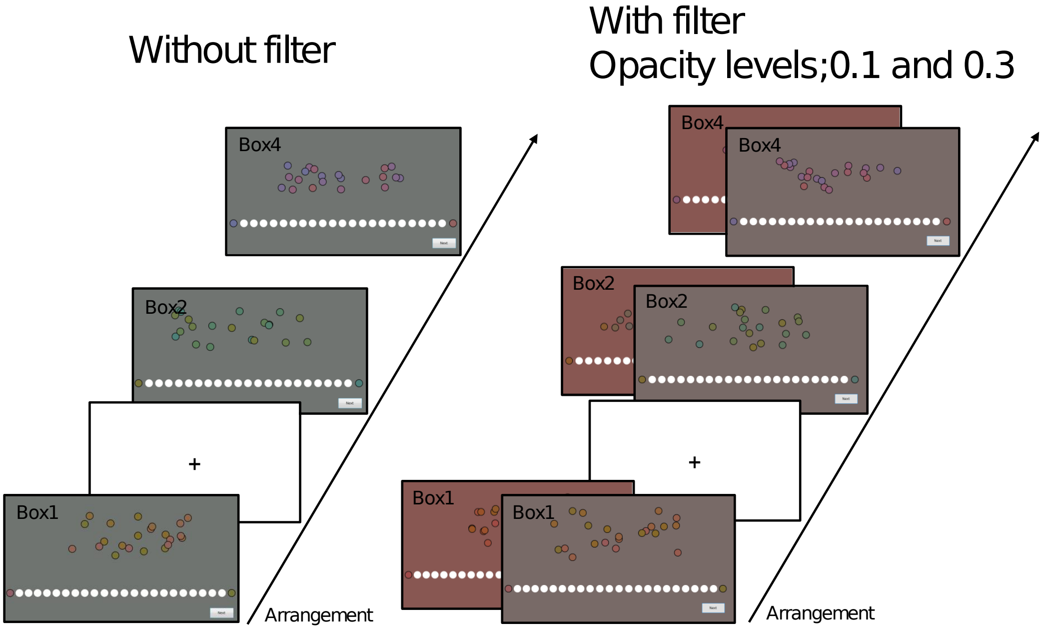

Figure 3. *Overview of experimental flow*

method proposed by Vingrys & King-Smith (1988)[16]. This method calculates the moment of inertia using the color difference vector of the obtained arrangement pattern. The C-index is one of the factors yielded by this method and can be used to estimate the severity of color confusion. This index is calculated the “two principal axes” from the color difference vector to identify the maximum and minimum radii. Vingrys & King-Smith (1988) reported that an index exceeding 1.77 is expected to be an anomalous arrangement, with a range of values as high as 3.06 to 4.21 for dichromat. However, because approximately 17% of CVD observers may pass the D-15 test, it is difficult to determine a cutoff point and correctly classify observers as normal or CVD observers (Dain & Adams, 1990)[17].

Figure 4 shows the two trial averages of the C-index for each filter condition for each participant. We present only the results of a single trial for D1 owing to time and date constraints. The results for the deutan observers (D1, D2, and D3) and one protan observer (P2) show that the discrimination performances tend to be improved in the filter condition with an opacity level of 0.1, compared with the 0.3 condition, although individual differences are observed. For D1 and D3, the discrimination performance was improved under the ColorMax D5 (D) filter with an opacity of 0.3. For the protans, the discrimination performance of P1 did not improve in any of the conditions with filters compared with the condition without filters. However, the discrimination performance of P2 improved in the condition with filters of opacity 0.1, compared with the condition without filters. In particular, the D filter demonstrated the best improvement. These results indicate that the three types of filters, except for the ChromaGen Y (Y) filter, improved the discrimination performance of protan observers. By contrast, among deutan observers, the X-Chrom (X) filter improved the discrimination performance of only deuteranopes.

Discussion

Sato et al. simulated the red filter, which is equivalent to the X filter in this study, based on the spectral transmittance of a lens similar to the X-Chrom lens, and then evaluated the filter

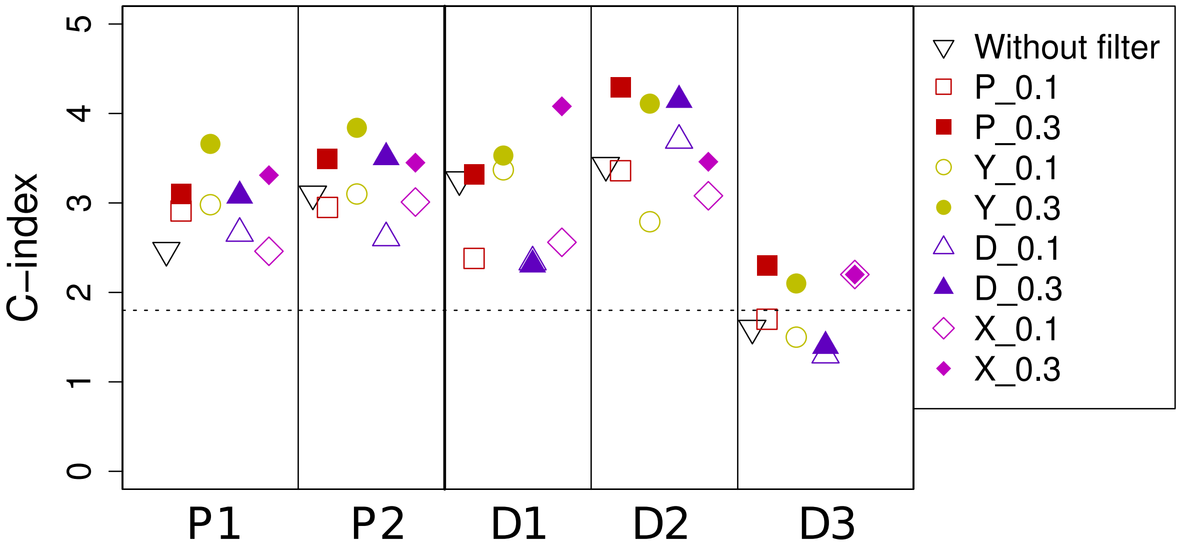

Figure 4. *C-index without and with filter conditions for opacity levels 0.1 and 0.3*

using the D-15 test. The simulated filter improved the discrimination performance of deutan observers but deteriorated that of protanopes [12]. In similar to the results of Sato et al's study, out experiment showed that the X filter did not remarkably improved the performance of protan observers.

We compared our results with those of a previous study that evaluated the effects of colored filters. Gómez-Robledo et al. performed a 100-hue test on CVD observers to evaluate the efficacy of Enchroma glasses [10]. The Enchroma glasses comprised an overall filter that was approximately blue owing to a notched filter that absorbed only the overlapping region of red and green light. The Enchroma glasses did not yield significant improvements in the 100-hue test. By contrast, the present experiment suggests that three types of filters, except for the Y (ChromaGen Y) filter, are effective in improving the color discrimination ability of protan observers. The difference among the P (ChromaGen P), D (ColorMax D5), and X (X-Chrom) filters used in this experiment and the Enchroma glasses is that the latter absorb only wavelengths in the 570-600 nm range, whereas the three filters absorb the wavelengths in the 500-600 nm range.

Swarbrick et al. used the D-15 test to evaluate ChromaGen lenses, which can adjust the color to accommodate CVD observers. Participants of the experiment were allowed to select the color of the ChromaGen lenses. The result shows that the discrimination performance of deutan observers improved; however, that of the protan observers was not affected [18]. Oli et al. evaluated the effectiveness of a red contact lens for red-green CVD observers via the D-15 test. Similar to ChromaGen, the red contact lens was fabricated using poly-2-hydroxyethyl methacrylate. The results show improved performance in the observers who wore the red contact lens [19].

In a study by Martínez-Domingo et al., red-green CVD observers were instructed to perform the 100-hue test while wearing dark purple VINO glasses [11]. However, their performances did not improve. According to Martínez-Domingo et al., this occurred because the glasses darkened the entire visual field. In our experiment, this effect was observed when relatively transparent filters were used. This suggests that the simulated filters with low opacity levels can improve discrimination performance. The characteristics of the filter that improved the discrimination performance, as shown in Figure 1, suggest that filters that transmit long wavelengths (600-700 nm) and absorb medium wavelengths (500-600 nm) may improve the performances of protan and deutan observers.

This study had several limitations. First, the filters were simulated based on the spectral-transmittance-based colored filters used in Diaconu and Moreland's study [13][14] using a standard observer color matching function. This can only be justified for normal observers and not for red-green CVD observers. Additionally, the color stimuli of the 100-hue test were translated to tristimulus values X, Y, and Z based on the color matching function for a standard observer. Hence, both the filter and color stimuli simulated in this study did not consider the perception experienced by CVD observers for the actual filter or color stimuli. For this reason, it should be noted that our results are not ecologically valid in the natural scenes.Second, the symptoms and severity of red-green color-vision deficiency vary. Because only five participants were involved in the study, the present results may not be realistic owing to the small sample size, conservative distribution of red-green CVD participants, and insufficient genetic confirmation. Further studies involving larger groups of observers with different types and severities of color-vision deficiency should be conducted to clarify the general characteristics of color in red-green CVD observers more comprehensively.

Conclusion

In this study, we digitally simulated colored filters based on the spectral transmittance of four colored filters, which have been used previously. To verify the discrimination performance of red-green CVD observers through the simulated filters, five red-green CVD observers were subjected to the 100-hue test on a monitor under nine filter conditions, including one condition without filters and eight conditions with filters. Based on the filter arrangement, we quantified the discrimination performance using the C-index. The results indicated that a filter that transmits long wavelengths and absorbs medium wavelengths may improve the color discrimination performance of protan and deutan observers.

Appendix

Table 2 shows the u^*v^* reference values and the XYZ tristimulus measured values, which were measured with a colorimeter (EIZO EX2, EIZO Corporation)

References

[1] V. C. Smith, and J. Pokorny, Color matching and color discrimination, The science of color(2nded), ed. SHEVELL S.K, pp. 103-148(2003).

[2] J. M. Steward, and B. L. Cole, What do color vision defectives say about everyday tasks?, Optometry and vision science, 66, 5, pp. 288-295(1989).

[3] B. L. Cole, The handicap of abnormal colour vision, Clinical and Experimental Optometry, 87, 4-5, pp. 258-275(2004).

[4] A. Seebeck, Ueber den bei manchen Personen vorkommenden Mangel an Farbensinn, Annalen der Physik, 118, pp. 177-233(1837).

[5] J. C. Maxwell, 1. Experiments on Colour as perceived by the Eye, with Remarks on Colour-Blindness, Earth and Environmental Science Transactions of The Royal Society of Edinburgh, 21, pp. 275-298(1857).

[6] H. I. Zelter, The X-Chrom lens. Journal of the American Optometric Association, 42, pp. 933-937(1971).

[7] D. Harris, ChromaGen Clinical Procedures, Chromagen, Wirral, UK, 1997.

[8] A. R. Badawy, M. U. Hassan, M. Elsherif, Z. Ahmed, A. K. Yetisen and H. Butt, Contact lenses for color blindness, Advanced healthcare materials, 7, 12, 1800152(2018).

[9] J. K. Hovis, Long wavelength pass filters designed for the management of color vision deficiencies, Optometry and vision science, 74, 4, pp. 222-230(1997).

[10] L. Gómez-Robledo, E. M. Valero, R. Huertas, M. A. Martínez-Domingo and J. Hernández-Andrés, Do EnChroma glasses improve color vision for colorblind subjects?, Optics express, 26, 22, pp. 28693-28703(2018).

[11] M. A. Martínez-Domingo, L. Gómez-Robledo, E. M. Valero, R. Huertas, J. Hernández-Andrés, S. Ezpeleta and E. Hita, Assessment of VINO filters for correcting red-green Color Vision Deficiency, Optics express, 27, 13, pp. 17954-17967(2019).

[12] K. Sato, T. Inoue, S. Tamura and H. Takimoto, Discrimination of colors by red-green color vision-deficient observers through digitally generated red filter, Visual Neuroscience, 36(2019).

[13] V. Diaconu, D. Sullivan, J. F. Bouchard and V. Vucea, Discriminating colors through a red filter by protanopes and colour normal, Ophthalmic and Physiological Optics, 30, 1, p. 66-75 (2010).

[14] J. D. Moreland, S. Westland, V. Cheung and S. J. Dain, Quantitative assessment of commercial filter 'aids' for red-green colour defectives, Ophthalmic and Physiological Optics, 30, 5, pp. 685-692(2010)

[15] Japanese Industrial Standards(1999). JIS Z 8701

[16] A. J. Vingrys and P. E. King-Smith, A quantitative scoring technique for panel tests of color vision, Investigative Ophthalmology & Visual Science, 29, 1, pp. 50-63(1988).

[17] S. J. Dain and A. J. Adams, Comparison of the standard and Adams desaturated D-15 tests with congenital colour vision deficiencies, Ophthalmic and Physiological Optics, 10, 1, pp. 40-45(1990).

[18] H. A. Swarbrick, P. Nguyen, T. Nguyen and P. Pham, The ChromaGen contact lens system: colour vision test results and subjective responses, Ophthalmic and Physiological Optics, 21, 3, pp. 182-196(2001).

[19] A. Oli and D. Joshi, Efficacy of red contact lens in improving colorvision test performance based on Ishihara, Farnsworth D15, and Martin Lantern Test, medical journal armed forces india, 75, 4, pp. 458-463(2019).

Table 2. u^*v^* values for the 100 hue test colored cap and the measured values of 85 color stimuli simulated on a visual display.

Cap No.	$u*$	$v*$	Measured values			Cap No.	$u*$	$v*$	Measured values		
			X	Y	Z				X	Y	Z
1	43.18	8.03	21.7	17.7	14.0	44	-31.44	-5.13	12.0	17.6	21.8
2	44.37	11.34	21.6	17.6	13.1	45	-32.26	-8.16	12.2	17.6	23.1
3	44.07	13.62	21.4	17.7	12.4	46	-29.86	-9.51	12.5	17.6	23.4
4	44.95	16.04	21.3	17.6	11.7	47	-31.13	-10.59	12.4	17.7	23.7
5	44.11	18.52	21.3	17.8	11.1	48	-31.04	-14.30	12.6	17.8	25.2
6	42.92	20.64	20.9	17.8	10.5	49	-29.10	-17.32	13.0	17.8	26.3
7	40.02	22.49	20.3	17.6	10.0	50	-29.67	-19.59	13.0	17.8	27.4
8	42.28	25.15	20.5	17.7	9.2	51	-28.61	-22.65	13.3	17.7	28.4
9	40.96	27.78	20.0	17.7	8.5	52	-27.76	-26.66	13.5	17.5	30.0
10	37.68	29.55	19.6	17.6	8.2	53	-26.31	-29.24	13.8	17.5	30.8
11	37.11	32.95	19.2	17.6	7.3	54	-23.16	-31.24	14.5	17.6	31.7
12	35.41	35.94	19.0	17.6	6.7	55	-21.31	-32.92	14.7	17.5	32.1
13	33.38	38.03	18.6	17.6	6.2	56	-19.15	-33.17	15.0	17.5	31.9
14	30.88	39.59	18.3	17.8	6.0	57	-16.00	-34.90	15.7	17.5	32.9
15	28.99	43.07	18.0	17.9	5.4	58	-14.10	-35.21	15.8	17.3	32.7
16	25.00	44.12	17.3	17.6	5.2	59	-12.47	-35.84	16.3	17.6	33.3
17	22.87	46.44	16.8	17.6	4.7	60	-10.55	-37.74	16.5	17.3	33.6
18	18.86	45.87	16.6	17.8	5.1	61	-8.49	-34.78	16.8	17.4	32.4
19	15.47	44.97	16.1	17.8	5.4	62	-7.21	-35.44	16.9	17.4	32.7
20	13.01	42.12	16.0	17.6	6.0	63	-5.16	-37.08	17.3	17.4	33.3
21	10.91	42.85	15.6	17.6	5.9	64	-3.00	-35.95	17.6	17.3	32.7
22	8.49	41.35	15.3	17.7	6.4	65	-0.31	-33.94	17.9	17.4	31.6
23	3.11	41.70	14.8	17.8	6.6	66	1.55	-34.50	18.2	17.3	31.8
24	0.68	39.23	14.6	17.8	7.3	67	3.68	-30.63	18.3	17.4	30.0
25	-1.70	39.23	14.2	17.7	7.3	68	5.88	-31.18	18.7	17.4	30.3
26	-4.14	36.66	14.0	17.7	8.1	69	8.46	-29.46	19.0	17.5	29.5
27	-6.57	32.41	13.9	17.7	9.1	70	9.75	-29.46	19.1	17.3	29.0
28	-8.52	33.19	13.6	17.7	9.1	71	12.24	-27.35	19.4	17.4	28.2
29	-10.98	31.47	13.4	17.7	9.7	72	15.61	-25.68	19.8	17.4	27.4
30	-15.07	27.89	13.0	17.7	10.7	73	19.63	-24.79	20.3	17.4	26.6
31	-17.13	26.31	12.9	17.9	11.4	74	21.20	-22.83	20.3	17.4	25.8
32	-19.39	23.82	12.6	17.7	12.0	75	25.60	-20.51	20.9	17.4	24.7
33	-21.93	22.52	12.3	17.7	12.5	76	26.94	-18.40	21.0	17.4	24.1
34	-23.40	20.14	12.2	17.7	13.4	77	29.39	-16.29	21.1	17.4	22.9
35	-25.32	17.76	12.1	17.7	14.1	78	32.93	-12.30	21.2	17.3	21.3
36	-25.10	13.29	12.3	17.7	15.5	79	34.96	-11.57	21.6	17.4	20.9
37	-26.58	11.87	12.2	17.8	16.0	80	38.24	-8.88	21.9	17.4	20.0
38	-27.35	9.52	12.1	17.7	16.8	81	39.06	-6.81	21.8	17.4	18.9
39	-28.41	7.26	12.0	17.7	17.4	82	39.51	-3.03	21.8	17.5	17.9
40	-29.54	5.10	11.9	17.6	18.2	83	40.90	-1.50	21.8	17.4	17.2
41	-30.37	2.63	11.9	17.7	19.1	84	42.80	0.60	21.9	17.5	16.4
42	-31.07	0.10	12.0	17.8	20.2	85	43.57	4.76	21.6	17.4	15.0
43	-31.72	-2.42	12.1	17.8	21.1	BG			16.1	17.6	18.7