Performance of various color difference models in challenging regions of CIELAB color space

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Abstract

To examine the performance of a select group of advanced color difference equations against visual color difference data, we report the development of a combined visual dataset consisting of samples in the CIE low and high chroma blue color centers (NCSU-B1 [1] and NCSU-B2 [2]), a recent set of near black samples (NCSU-BK) [3] and a new dataset around a gray center (L^*=50.56, a^*=-0.11, b^*=0.03), hereafter called NCSU-Gr, using the gray scale method. The new gray dataset consisted of 21 matte painted samples, and the visual difference between each of the samples against the standard was assessed by 35 color normal observers under highly controlled viewing and illumination conditions and using the AATCC gray scales, in three separate sittings, and a total of 2205 assessments were obtained. The performance of two groups of color difference equations consisting of: 1- those based on CIELAB color space and 2- those based on more uniform color spaces/appearance model such as DIN, CIECAM02 and OSA, against the visual dataset was examined for the NCSU-Gr, and also for the combined dataset (NCSU-COM). The results show that CIEDE2000 (2:1:1) exhibits the best performance for the NCSU-Gr dataset in comparison to other equations examined. This confirms that the G term in the CIEDE2000 significantly improves its performance in the near neutral gray region. An examination of the performance of the models against the combined dataset, however, shows that the more uniform color space/appearance models produce better results than models based on CIELAB color space, with CAM02-SCD performing significantly better than other equations except CAM02-UCS.

Keywords: color difference, visual dataset, statistical significance, gray, color center, CAM02-SCD

Introduction

Color difference modeling is and continues to be one of the most important areas of colorimetry. Its ultimate goal is to generate a single number that can accurately predict the average visual color difference. CIELAB color difference formula, ΔE_{ab}^*, based on the CIELAB color space, is simply the Euclidian distance of two colors in the space, assuming the space is perceptually uniform and that the contribution of hue, chroma and lightness difference components to the overall color difference is the same. However, it is well known that the CIELAB color space is not perceptually uniform, and that the 3D volume representing unit visual difference, is not a sphere but an ellipsoid.

With a view to improving the performance of color difference models and enhancing their agreement against visual datasets several modifications have been introduced, over the years, to the basic model resulting in the CMC (l:c) [1], BFD (l:c) [2, 3], CIE94 [4] and CIEDE2000 [5] color difference equations, among others. These formulas have been optimized against specific datasets, and not surprisingly produce different predictions for color pairs located in different regions of the color space. Areas of particular interest are the blue and near neutral regions where many models fail to generate reasonably accurate predictions. The ellipses of near neutral colors on the a^*b^* plane are not oriented toward the origin but are vertically aligned to a^* axis, and those in the blue region are titled away from the radiant lines [6]. Among various color difference models only the latest CIE recommended color difference equation, CIEDE2000, accounts for both of these effects by rescaling the a^* axis for the near neutral colors, and introducing a rotation term, R_T, an interactive term between the hue and chroma difference, for blue colors [6].

In recent years, a series of color difference models based on more uniform color space and color appearance models have also been developed which include DIN99d [7], OSA-GP [8], OSA-Eu [9], CAM02-SCD [10], and CAM02-UCS [10]. It has been demonstrated that these formulas give better or comparable performances than CIEDE2000 for various visual datasets [11, 12]. The purpose of this study is twofold. First we introduce a new visual color difference dataset (NCSU-Gr) around a gray center (L^*= 50.56, a^*= -0.11, b^*= 0.03), using the gray scale method, incorporating the evaluation of performance of select advanced color difference equations for the gray dataset; and second we report the results of testing various color difference models based on CIELAB and more uniform color space/color appearance models against the combined dataset (NCSU-COM) which incorporates samples from regions of the CIELAB color space that are considered challenging when predicting color differences based on various models. The aim is to provide an up-to-date analysis of the performance of color difference models for suprathreshold small color differences.

Experimental Procedure

Description and Measurement of Samples

A total of 21 matte painted samples around the center (L^*=50.56, a^*=-0.11, b^*=0.03) was selected from a pool of gray samples. Samples were cut to 2×2" dimensions with sharp edges. A DataColor SF600X spectrophotometer was used to measure the reflectance of all samples using a large area view aperture (30mm), and excluding UV and specular light. All samples were measured 4 times, with a 90 degree rotation between measurements, and the average reading was obtained. CIE illuminant D65 and CIE 1964 Supplementary Colorimetric Observer were used for all colorimetric calculations. The distribution of samples in the CIELAB space is shown in Figure 1. Samples slightly varied in terms of hue, chroma and lightness, with lightness differences ranging from 49 to 51, chroma differences from 0.11 to 1.39 and hue differences representing different regions of the hue circle. The 21 sample pairs had an average ΔE^*_{ab} of 2.06 against the standard, with a range of 0.69-2.83 and a standard deviation of 0.58.

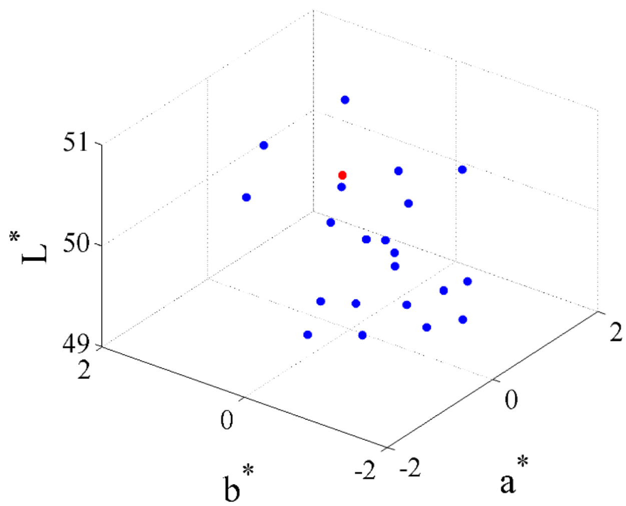

Figure 1 Distribution of gray samples in the CIELAB space (red dot denotes standard)

Methodology

For visual assessments, a custom sample stand, based on a 45/0 degree illumination-viewing geometry, was manufactured and painted to approximately Munsell neutral gray N7.25 to match the color of the interior of the viewing booth. The stand was used to house the standard and test samples as well as an AATCC gray scale for color change [13], as shown in Fig.2.

The observers (13M and 22F) ranged from 19 to 33 years of age, with an average age of 23.2. Of the 35 observers, 17 were Caucasian, 2 were African American, and 15 were of Asian origin. All observers had normal color vision according to the Ishihara confusion plates test results, and most of them were naïve for the purposes of the experiment with majority having 0 to 1 year prior experience in color assessments. Nine observers had more than 1 year experience in visual assessment of color.

In the selection of 21 samples used in the dataset, the overall contribution of each sample's differences against the standard in terms of lightness, chroma, hue, and their combinations to the total difference was considered, as shown in Table 1. Three subsets were considered, with subsets 1-2 comprising samples with either lightness, or chroma differences representing more than 70% of the overall difference, respectively. Subset 3 comprised samples with significant contribution of colorimetric components (hue, chroma and lightness) to the total color difference.

Table 1, Relative contribution of lightness, chroma, and hue differences to overall ΔE^*_{ab} in NCSU-Gr dataset.

Subset	$\Delta L^{*2}/\Delta E^{*}_{ab}{}^{2}$	$\Delta C^{*2}/\Delta E^{*}_{ab}{}^{2}$	$\Delta H^{*2}/\Delta E^{*}_{ab}{}^{2}$	No of Samples
1	79.2	14.9	6.0	6
2	9.3	76.8	13.9	9
3	38.3	41.0	20.8	6

Each observer assessed samples three times with at least 24 hours gap between assessments. During the assessment observers wore a mid-gray laboratory coat and a pair of gray gloves to minimize color variability of the surround during the course of the experiment and to prevent damaging the samples. The samples were placed by the experimenter who also wore a mid-gray laboratory coat. At the beginning of the experiment, the observer viewed the empty illuminated viewing booth for 2 minutes to adapt to the light source; during which time the experiment was explained. The AATCC Gray Scale for Color Change was placed directly below the standard and sample pair. During the assessment, observer gave a rating for the visual difference (ΔV) between each sample and standard according to AATCC Gray Scale contrast ratings from 1 to 5, including intermediate values, e.g. 2-3. The nine contrast pairs on the AATCC scale are perceptually geometrically scaled with scale 5 denoting no difference between samples (ΔE^*_{ab} = 0 - 0.2), while 1 signifying a large difference (ΔE^*_{ab} = 13.1±1). Observers were asked to give a decimal rating for each pair, e.g. 3.2 if they considered the pair's difference to be less than 3-4 based on the gray scale rating but higher than 3. The visual assessments were conducted under well controlled viewing and illumination conditions using a SpectraLight III (X-Rite) viewing booth equipped with filtered incandescent daylight simulators. Extraneous light was excluded during the assessments.

The illumination conditions were measured using a PR-670 SpectraScan Spectroradiometer (Photo Research, Inc.), and a PTFE standard white tile. The illumination in the middle of the booth was 1404 lux with a correlated color temperate (CCT) of 6504K.

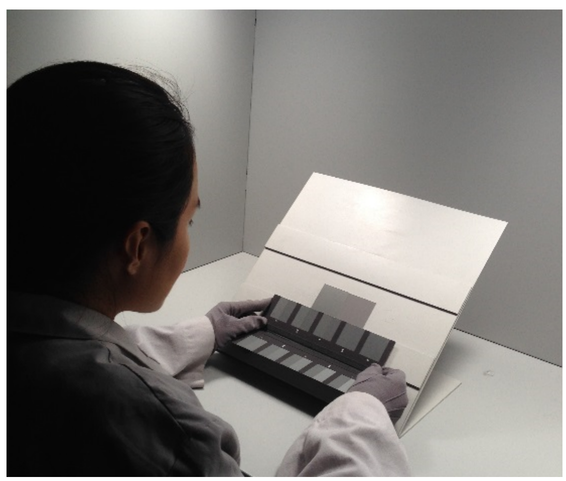

Figure 2 The viewing and illumination conditions employed in visual assessments using a SpectraLight III viewing booth

The color difference, ΔE^*_{ab}, for each of the AATCC contrast pairs was also measured using the conditions described for the measurement of sample pairs. A third degree polynomial equation was used to convert the AATCC standard gray scale ratings, G, to visual differences (ΔV) [1-3]. The polynomial function is given in Equation 1.

$$\Delta V = -0.2201G3 + 2.7424G2 - 12.91G + 23.559 \quad (1)$$

The R² value for the polynomial fitting used is 0.998, indicating a high correlation. The Standardized Residual Sum of Squares (*STRESS*) index [14] was used to evaluate the performance of color difference equations.

Results and Discussion

Inter- and intra-observer variability

It was assumed that the mean values were the 'true' values for each pair. The perceptual data used in the *STRESS* calculations of this experiment were based on the gray scale ratings after conversion to visual differences. The *STRESS* values representing observers' repeatability and reproducibility are shown in Table 2 and Figure 3. The mean inter-observer variability was 22.73 units ranging from 11.54 to 45.09. One method to screen outliers is to compare the variability in responses amongst observers. In this study the inter-observer variability of two observers was found to be larger than the remaining observers. However, these observers were not excluded in calculations and their intra-observer variability was found to be similar to others in the group. Results demonstrate that observers' repeatability of assessments had a relatively large range. In a previous study it was shown that assessments made by naive observers track that of experts well, though a statistically significant difference in judgments between naïve and expert subjects was also noted [17].

To determine whether differences in experience among subjects affected the variability average inter- and intra-variability for the nine experienced and the remaining inexperienced observers was calculated and compared. The average inter-observer variability for experienced observers is 20.46 compared to 23.54 for the remaining observers. The intra-observer variability for the two groups was similar, with 24.24 for experienced observers and 25.64 for the remaining. In addition, 17 observers showed a reduction in STRESS values from trial 1 to both trials 2 and 3. For unknown reasons intra-variability for 1 experienced and 8 naïve observers was larger in trials 2 and 3 compared to trial 1.

Evaluation of the performance of color difference formulas for the NCSU-Gr dataset

In this study, 10 color difference formulas with different parametric factors, resulting in 14 different combinations, were examined. The parameters used in the CIECAM02 based color difference equations are: L_A = 89.1 cd/m^2; Y_b = 44.4; c = 0.69; Nc = 1.0; and F = 1.0. The STRESS values for each formula for the visual datasets are shown in Table 3. The F-test using the STRESS function was employed to determine the significance of variation in results between two formulas at 95% confidence level [15], and the results are shown in Table 4. Results with pink background denote the model shown in the column performs significantly worse than that in the row, while values in with light blue background signify the model in the row performs significantly better than that given in the column.

Table 2 STRESS values representing intra-observer variability in three trials for the NCSU-Gr dataset.

Observer	*Trial 1*	*Trial 2*	*Trial 3*
1	30.97	40.52	34.93
2	30.77	19.59	14.39
3	12.98	13.00	11.94
4	37.85	27.18	34.57
5	31.37	26.20	33.47
6	23.54	16.29	23.97
7	39.07	26.66	34.71
8	22.52	19.34	18.07
9	15.58	14.96	15.46
10	26.17	22.13	21.57
11	27.57	21.49	19.75
12	18.92	11.85	20.21
13	18.21	24.18	20.32
14	21.64	20.42	20.28
15	21.49	17.53	25.96
16	24.98	18.71	17.02
17	24.74	36.24	31.18
18	28.99	28.99	26.86
19	16.13	20.47	25.17
20	35.34	31.14	28.38
21	24.64	18.43	25.50
22	28.64	30.35	32.12
23	21.73	24.23	20.88
24	33.17	31.65	23.77
25	33.28	32.15	37.03
26	24.86	30.76	27.54
27	15.99	20.30	25.76
28	19.19	21.49	20.14
29	29.49	32.02	33.02
30	20.07	23.08	18.45
31	29.30	22.96	27.66
32	26.48	18.87	32.56
33	35.23	27.16	24.70
34	26.71	20.92	31.49
35	40.38	38.01	28.39

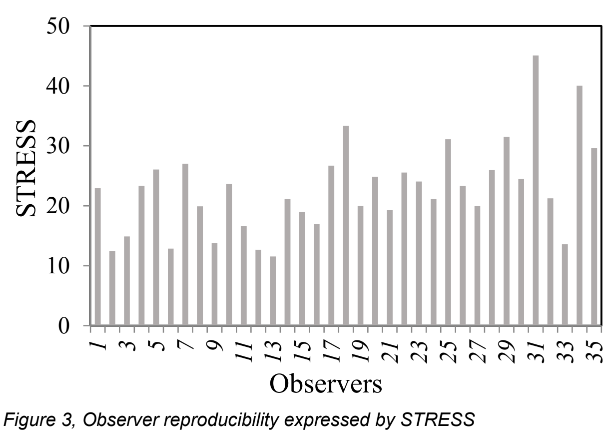

Figure 3, Observer reproducibility expressed by STRESS

Results in Table 3 show that CIEDE2000 (2:1:1) gives the best performance among all models examined for the gray dataset developed with a STRESS value of 11.79. The CIEDE2000 model is optimized against a background lightness of 50 and thus the good performance of the model for this gray set is not surprising. This is followed by CMC (1:1) and CIE94 (2:1). All three equations significantly outperformed CIELAB and CIE94 (1:1) as shown in Table 4.

The parametric factor k_L in CIEDE2000/CIE94 or *l* in CMC can be adjusted to account for the surface characteristics of the samples, such as texture, and is usually set to 1 for flat samples [16]. However, adjusting this parameter to 1 in CIEDE2000 and CIE94, for this gray dataset, results in models showing inferior performance compared to k_L or *l* of 2. k_L or *l* can be optimized for various equations to determine whether the performance of models could be improved. This was achieved via minimizing the STESS for each color difference equation, though there is no explicit k_L term in DIN99d, OSA_Eu and OSA_GP equations. The k_L with asterisk in the tables denotes the optimized value. From Table 3, it can be noticed that formulas with optimized k_L did not significantly outperform models at k_L or *l* of 1 or 2 except for CIE94. The optimized version of CMC, DIN00d and OSA_GP are significantly better than CIELAB and CIE94 (1:1) though its k_L or *l* of 1 or 2 version did not.

Table 3 STRESS values between ΔV and ΔE for various color difference formulas for the NCSU-Gr dataset at k_L or l of 1, 2 and optimized* k_L value.

Color Difference Model	k_L or *l*	STRESS
CIELAB	-	20.08
CMC	1	13.14
	2	14.10
	*1.19	12.77
BFD	1	12.72
	2	13.14
	*1.1	12.58
CIE94	1	20.17
	2	12.77
	*2.04	12.76
CIEDE2000	1	15.98
	2	11.79
	*1.7	11.62
DIN 99d	1	13.54
	*1.35	12.37
CAM02UCS	1	19.53
	*1.54	17.67
CAM02SCD	1.24	18.01
	*1.57	17.54
OSA_Eu	1	12.88
	*1.33	12.70
OSA_GP	1	13.48
	*1.23	12.93

In order to determine the effect of various components in advanced color difference models based on CIELAB including CMC, CIE94, BFD and CIEDE2000, their reduced forms were also examined. The reduced forms were obtained by removing the corresponding functions [17]. Since the rotation term in BFD and CIEDE2000 models is used to adjust the performance of models for blue colors, this term was not examined for the gray dataset developed. Results are shown in Table 5. The asterisk in the last row means the difference between the full model and the reduced form is statistically significant.

Table 5 STRESS values for CIEDE2000, CIE94, CMC, BFD and their reduced forms for NCSU-Gr.

Color Difference Model	(k_L:k_C:k_H) or (*l*:*c*)	
	(1:1:1)/ (1:1)	(2:1:1)/(2:1)
CMC: Full Model	13.14	14.10
-Lightness	13.67	13.79
-Chroma	16.88	13.54
-Hue	14.17	15.12
CIE94: Full Model	20.17	12.77
-Chroma	20.08	12.78
-Hue	20.16	12.77
BFD: Full Model	12.72	13.14
-Chroma	18.02	14.69
-Hue	14.05	14.47
CIEDE2000: Full Model	15.98	11.79
-Lightness	15.98	11.79
-Chroma	15.58	12.17
-Hue	15.93	11.79
-G term	20.62	12.65

Results in Table 5 show that in the case of the CMC(1:1) model the incorporation of chroma and hue modifications has resulted in improving the performance of the equation. However, when the (*l*:*c*) ratio is set to 2:1 removing the lightness and chroma terms actually slightly improves the performance of the model, while removing the hue term deteriorates the performance by nearly 1 STRESS unit. In the case of the CIE94 formula, in either setting removing the chroma and hue terms does not change the performance. In the case of the BFD model, both chroma and hue components improve the performance of the model though results are more pronounced for the 1:1 rather than 1:2 ratios. In the case of the CIEDE2000 model, removing lightness, chroma and hue terms does not seem to alter the performance for the (1:1:1) ratio, but removing the G term, which is specially designed to improve the performance in the near neutral region, exerts a significant deterioration in performance of the model. Removing any of these terms results in inferior performance of the CIEDE2000 (2:1:1) model, and removing the G-term causes a statistically significant reduction in its performance. It is thus evident that the G term is highly effective in improving the performance of the CIEDE2000 model for near neutral gray samples.

Evaluation of the performance of color difference formulas for the NCSU-COM dataset

The performance of color difference equations was examined for the combined dataset, NCSU-COM, as shown in Table 7. The details of each dataset can be found elsewhere [12, 18, 19]. F-test was used for the statistical analysis and the results are examined.

Results in Table 7 indicate that color difference equations based on CIECAM02 gave a better performance than that for all other models examined with non-optimized k_L or l value. Furthermore, they significantly outperform all models with the exception that CAM02SCD was not statistically better than BFD(2:1), CIE94(2:1), CIEDE2000(1:1:1) or OSA-GP. In general, except for OSA-Eu all other uniform color space based equations gave smaller STRESS values compared to CIELAB based color difference equations.

Surprisingly the performance of CMC equation was found to be apparently worse than that of CIELAB. A speculation is that the STRESS index is sensitive to the distribution of data, and the number of samples [20]. However, using the correlation coefficient to analyze results did not make a difference in the outcome.

A detailed F statistical analysis of results for the NCSU-COM is not shown but Results for that dataset and for NCSU-Gr indicate that the performance of the models based on setting k_L or l to 1 for flat and 2 for textile samples is not consistent, *e.g.* CIEDE2000(2:1:1) gives a better performance for gray dataset while it gives a worse performance for the NCSU-COM dataset.

Results in Table 7 indicate that CIEDE2000 and OSA_Eu, based on optimized k_L, statistically significantly outperform CIELAB and CAM02UCS models.

Table 7 STRESS for the NCSU-COM dataset at various k_L or l settings.

Color Difference Model	k_L or l	STRESS
CIELAB	-	38.79
CMC	1	50.39
	2	43.00
	*2.65	42.45
BFD	1	36.50
	2	35.87
	*1.30	35.65
CIE94	1	38.24
	2	34.51
	1.75	34.33
CIEDE2000	1	33.58
	2	36.88
	*1.02	33.57
DIN 99d	1	34.47
	*1.39	33.05
CAM02UCS	1	28.84
	*1.19	28.28
CAM02SCD	1.24	31.16
	*1.22	31.15
OSA_Eu	1	37.13
	*1.67	33.25
OSA_GP	1	33.00
	*1.49	30.25

Conclusions

A visual color difference dataset, NCSU-Gr, around a gray color center (L^*=50.56, a^*=-0.11, b^*=0.03) was developed and STRESS index was used to compare the performance of two groups of color difference equations- those based on CIELAB color space and those based on more uniform color space/appearance models. The reduced models of CMC, BFD, CIE94 and CIEDE2000 were also examined. A combined NCSU-COM dataset incorporating NCSU-B1, NCSU-B2 and NCSU-BK as well as NCSU-Gr is also introduced. This dataset includes samples from regions of the color space where traditionally most models fail to provide accurate predictions. The performance of various color difference equations against the combined NCSU dataset was also examined.

CIEDE2000 (2:1:1) gave the best performance for the NCSU-Gr dataset, and the G term was found to significantly improve the performance of this model.

For the combined NCSU dataset, more uniform color space based equations, except OSA-Eu, were found to give better performances than those based on CIELAB color space. CAM02-UCS and CAM02-SCD significantly outperformed most color difference equations for the combined dataset.

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Author Biography

Renzo Shamey is the Director of the Polymer and Color Chemistry program and Color Science and Imaging Laboratory at North Carolina State University. He is a Professor of Color Science, a Fellow of the Society of Dyers and Colourists, and author of well over 100 manuscripts. He is active in the CIE Division 1 committees 55, 76, 77 and currently chairs the AATCC RA36 Color Measurement Test Methods Committee.

Mr. Renbo Cao, Ms Weethima Sawatwarakul and Ms Juan Lin were PhD students in the Color Science and Imaging Group at North Carolina State University during the course of this study.

Table 4 F-test results of NCSU-Gr dataset (N=21, Fc=0.41)

	CIELAB	CMC			BFD			CIE94			CIEDE2000			DIN 99d		CAM02UCS		CAM02SCD		OSA_Eu		OSA_GP	
		(1:1)	(2:1)	(Kopt:1)	(1:1)	(2:1)	(Kopt:1)	(1:1)	(2:1)	(Kopt:1)	(1:1:1)	(2:1:1)	(Kopt:1:1)	1	Kopt	1	Kopt	1.24	Kopt	1	Kopt	1	Kopt
CIELAB	1.00																						
CMC(1:1)	0.43	1.00																					
CMC(2:1)	0.49	1.15	1.00																				
CMC(K_{opt},1)	0.40	0.94	0.82	1.00																			
BFD(1:1)	0.40	0.94	0.81	0.99	1.00																		
BFD(2:1)	0.43	1.00	0.87	1.06	1.07	1.00																	
BFD(K_{opt},1)	0.39	0.92	0.80	0.97	0.98	0.92	1.00																
CIE94(1:1)	1.01	2.36	2.05	2.49	2.51	2.36	2.57	1.00															
CIE94(2:1)	0.40	0.94	0.82	1.00	1.01	0.94	1.03	0.40	1.00														
CIE94(K_{opt},1)	0.40	0.94	0.82	1.00	1.01	0.94	1.03	0.40	1.00	1.00													
CIEDE2000(1:1:1)	0.63	1.48	1.28	1.57	1.58	1.48	1.61	0.63	1.57	1.57	1.00												
CIEDE2000(2:1:1)	0.34	0.81	0.70	0.85	0.86	0.81	0.88	0.34	0.85	0.85	0.54	1.00											
CIEDE2000(K_{opt}:1:1)	0.33	0.78	0.68	0.83	0.83	0.78	0.85	0.33	0.83	0.83	0.53	0.97	1.00										
DIN 99d	0.45	1.06	0.92	1.12	1.13	1.06	1.16	0.45	1.12	1.13	0.72	1.32	1.36	1.00									
DIN99d(K_{opt})	0.38	0.89	0.77	0.94	0.95	0.89	0.97	0.38	0.94	0.94	0.60	1.10	1.13	0.83	1.00								
CAM02UCS	0.95	2.21	1.92	2.34	2.36	2.21	2.41	0.94	2.34	2.34	1.49	2.74	2.82	2.08	2.49	1.00							
CAM02UCS(K_{opt})	0.77	1.81	1.57	1.91	1.93	1.81	1.97	0.77	1.91	1.92	1.22	2.25	2.31	1.70	2.04	0.82	1.00						
CAM02SCD	0.80	1.88	1.63	1.99	2.00	1.88	2.05	0.80	1.99	1.99	1.27	2.33	2.40	1.77	2.12	0.85	1.04	1.00					
CAM02SCD(K_{opt})	0.76	1.78	1.55	1.89	1.90	1.78	1.94	0.76	1.89	1.89	1.20	2.21	2.28	1.68	2.01	0.81	0.99	0.95	1.00				
OSA_Eu	0.41	0.96	0.83	1.02	1.03	0.96	1.05	0.41	1.02	1.02	0.65	1.19	1.23	0.90	1.08	0.43	0.53	0.51	0.54	1.00			
OSA_Eu(K_{opt})	0.40	0.93	0.81	0.99	1.00	0.93	1.02	0.40	0.99	0.99	0.63	1.16	1.19	0.88	1.05	0.42	0.52	0.50	0.52	0.97	1.00		
OSA_GP	0.45	1.05	0.91	1.11	1.12	1.05	1.15	0.45	1.11	1.12	0.71	1.31	1.35	0.99	1.19	0.48	0.58	0.56	0.59	1.10	1.13	1.00	
OSA_GP(K_{opt})	0.41	0.97	0.84	1.03	1.03	0.97	1.06	0.41	1.03	1.03	0.65	1.20	1.24	0.91	1.09	0.44	0.54	0.52	0.54	1.01	1.04	0.92	1.00