J. Coat. Technol. Res., **13** (5) 871–882, 2016
DOI 10.1007/s11998-016-9790-8

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Colorimetric analysis of black coated fabrics

R. Jafari, S. H. Amirshahi, S. A. Hosseini Ravandi

Abstract In this article, two visual evaluation methods, i.e., the rank-ordering and pair comparison techniques, are sequentially used to investigate the effect of hue, lightness, and chroma values on the preference of blackness of 216 black coated fabrics. Based on the colorimetric attributes of specimens, the blackness preference of samples is assessed by 18 amateur observers through different predesigned experiments. Results show that while the lightness of samples performs a very important role in the blackness preference, it does not individually influence the results, and irrespective of the effect of chroma, observers perceive bluish-cyanish black fabrics as the preferred black samples. However, the specialized functionality of lightness is evident for black coated fabrics with very close hue and chroma attributes, and the blackness preference of samples increases when lightness is decreased. Finally, the validity of some suggested blackness indices is evaluated with comparison to the visual results.

Keywords Coated fabrics, Blackness, Pigments, Rank ordering, Pair comparison techniques

R. Jafari
Department of Color Physics, Institute for Color Science and Technology, 1668814811 Tehran, Iran

S. H. Amirshahi (✉)
Department of Textile Engineering, Amirkabir University of Technology (Tehran Polytechnic), 15914 Tehran, Iran
e-mail: hamirsha@aut.ac.ir

S. A. Hosseini Ravandi
Department of Textile Engineering, Isfahan University of Technology, 84156 Isfahan, Iran

Introduction

Evaluation of black objects has been interesting research topic over the years.[1–12] While producing deep blacks is an important target for different manufacturing products like textiles, paints, printings, and cosmetics,[4] few scientific investigations have been published which systemically studied the subject. Blackness has different meanings in various cultures and is symbolized differently by nations.[6] Through the inspiration of whiteness formulae, Westland et al. suggested four blackness indices for the assessment of different black inks. Among the different employed metrics, a non-linear model which considered the CIELAB colorimetric attributes of black papers showed the best correlation with the results of the visual assessment experiments.[4] Clonts et al. proposed two ranking and rating models to assess the perceived blackness based on the samples' hue angle and chroma while the lack of lightness is observed in both models.[5,9] In other work, Tao et al. investigated the effect of hue as well as value and chroma on blackness perception and preference by considering the observers' nationality and gender.[7,8] Recently, Jafari et al. tried to define the occupied volume of a set of deep gray and black samples based on the perceived blackness of a group of observers.[13] They showed the importance of hue angle, i.e., from 180° to 270°, in blackness perception.

Although there are some investigations that have tried to find a metric for the evaluation of blackness,[4,5,9] no accepted index has been agreed upon. To represent an index for assessment of black objects, it seems reasonable to first find the exact dimensions of spectral reflectance of blacks. The subject has been studied by Jafari et al.,[10] and they investigated the low spectral dimensions of black surfaces in different spectral spaces. From a physical point of view, they showed that a three-dimensional spectral space is enough to define the reflectance properties of such samples. However, the psychological impression of blacks could be different from their physical properties, and several factors such as the lightness, chroma, and the hue could affect the visual attributes of such samples.

Blackness perception

Among three steps of visual processing, i.e., early-, intermediate-, and high-level vision, corresponding to the sensation, perception, and cognition, the intermediate step is based on the human tendency to see the world as composed of objects and surfaces.[14] There is some information related to the object's properties and identities which is provided via vision though the spectral properties of the reflected light vary across the object's surface.[15] Besides, the characterization of mechanisms for mapping the luminance in the retinal image onto grayscale perception underlies any theory of surface lightness perception. Existing theories represent linear/nonlinear functions mapping the luminance to lightness. These models investigate the lightness perception mechanisms for grayscale surfaces with a variety of luminance factors while these surfaces obey the constant chromaticity and the hue.[16]

In this article, the authors investigate which chromatic contributors affect the blackness preference of a group of observers. To study the effect of different colorimetric attributes on the preferred blacks, a large set of black coated fabrics with identical texture was prepared that were benefited from different levels of lightness, chroma and hue, and the blacks have been visually assessed through a series of psychological experiment. In spite of some difficulties in the preparation of such real samples, this setup was preferred to the simulation of blacks on a monitor[7,8] or by near neutral samples of Munsell set[5,9] that have different textures and glossiness in comparison to textile materials.

Experimental

Materials

In order to investigate the influence of colorimetric properties of blacks on visual evaluations, 216 black samples with various levels of lightness, chroma, and hue were prepared on plain woven cotton fabrics via the routine textile pigment printing technique. To provide a complete set of blacks with different colorimetric attributes, different concentrations of four colored pigments, i.e., red, green, blue, and yellow, in addition to black pigment were used in various binary, tertiary, quadric, and quintuplet combinations. The classical full oil/water emulsion was used for the printing recipe, and the ammonium sulfate and acrylic binder were added to fix the printed fabrics. In this way, 216 black fabrics were totally coated by manual silk screen printing method. The commercial and the generic names of employed pigments are shown in Table 1.

The reflectance spectra of black coated fabrics within 400 to 700 nm at 10 nm intervals were measured using a reflectance spectrophotometer named Spectraflash from Datacolor that benefited from d/8 geometry. The CIEXYZ tristimulus values of samples were calculated under D65 standard illuminant and CIE1964 standard observer. The a*b* and C*L* scatter plots of samples are shown in Figs. 1 and 2, respectively.

As shown in Fig. 1, black fabrics have suitably covered the quadruplet areas of hue in a*b* plane. In addition, Fig. 2 indicates that black samples have different levels of chroma varying from 0.04 to 4.16 and lightness from 17.64 to 23.94.

Methods

The visual evaluation was performed by 18 observers including 9 females and 9 males in range of 21–27 years old. The normal color vision of the participants was approved by means of an Ishihara test prior to the

Table 1: Color indices and the supplier of pigments employed to coat the fabrics

Commercial name	Supplier	Generic name
Imperon Black FBB	Dystar	Pigment Black 7
Imperon Blue K-RR	Dystar	Pigment Blue 15
Imperon Green K-G	Dystar	Pigment Green 7
Imperon Yellow K-2G	Dystar	Pigment Yellow 14
Imperon Red K-GC	Dystar	Pigment Red

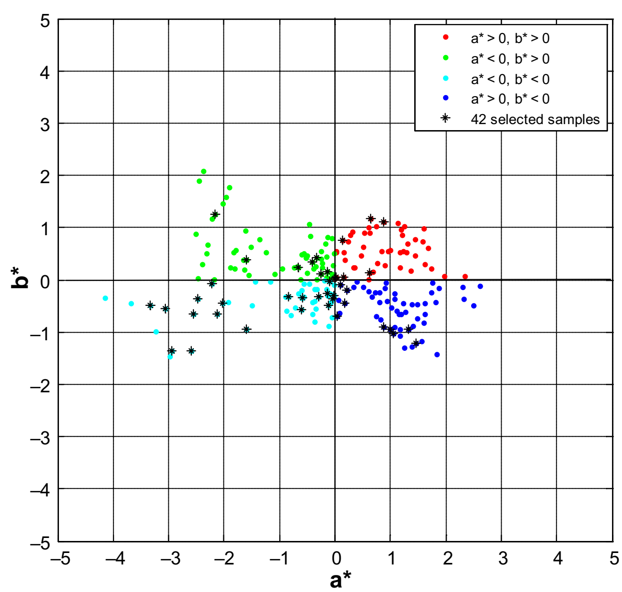

Fig. 1: The a*b* scatter plots of 216 black coated fabrics. The 42 selected samples are denoted by stars (asterisk)

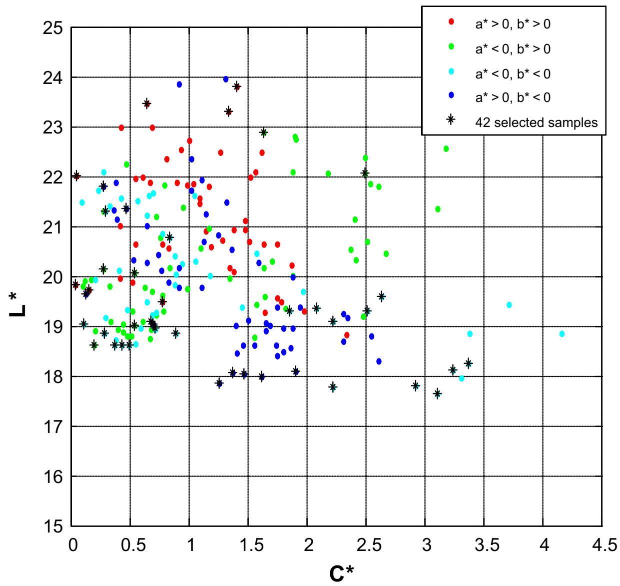

Fig. 2: The C*L* distribution of 216 black coated fabrics. Different colors denote the positions of samples in different quadrant areas, while black stars denote the 42 final selected samples

evaluation sequence. All visual evaluations were done under a VeriVide light booth (Model: CAC 120) with a medium gray background (L* = 42.55, a* = −1.34 and b* = 0.50). The light cabinet was equipped with a daylight simulator with correlated color temperature of 5940 °K and the CRI of 97. The sample size was 3 cm × 3 cm, and the distance between the observer and sample was fixed to 17 cm to approximately simulate the CIE 1964 supplementary standard observer (10° observer). The 0°/45° illuminant/observer arrangement was also used during the visual evaluation. The concept of blackness preference was described to observers, and they were asked to rank order the samples in initial rank-ordering effort or compare them as pairs in the final pair comparison trial.

While the preparation of 216 black samples practically provided the broad set of blacks, it absolutely took the chance of using the pair comparison method for the psychophysical evaluations of sample due to the huge number of available pairs. Hence, an initial rank-ordering method was first employed for pre-selection of the most preferred blacks within the designed subgroups. The employed evaluation methods were as follows:

Hue-based assessment (using rank-ordering method)

Samples were first clustered into different groups based on their hues. In fact, 216 black fabrics were classified into four different categories based on their positions in each quadrant of a*b* Cartesian plot. Therefore, according to the hue angle attributes of blacks, they were divided into 48, 60, 54, and 54 samples that, respectively, correspond to 0° ≤ h < 90°, 90° ≤ h < 180°, 180° ≤ h < 270°, and 270° ≤ h < 360° areas of hue. The rank-ordering method[17,18] was chosen to preliminarily evaluate the samples of each group. In this way, the samples were randomly represented to the observers, and they were asked to order them according to their blackness preference from minimum to maximum. Then, the average of assigned ranks given by 18 observers was supposed to be the order of samples and reported as the scale value of blacks. Finally, the three most pleasing blacks from each hue area (totally 12 samples) were selected for further evaluation.

Chroma-based assessment (using rank-ordering method)

The chroma attribute of black fabrics was considered to be the second criterion for the evaluation of blackness. In this way, 7 different areas of chroma were considered from the lowest to the highest by 0.5-step interval. By this norm, 42 black fabrics positioned in the first level (chroma <0.5), 61 samples placed in the second level (0.5 ≤ chroma < 1), 39 fabrics positioned in the third level of chroma (1 ≤ chroma < 1.5), and 42, 14, 9, and 9 samples located in the fourth, fifth, sixth, and seventh steps of chroma, respectively. Thus, the greatest magnitude of chroma was defined for the group of black fabrics with the chroma ≥3. Again, the samples were rank ordered from the lowest to the highest degree of blackness preference in each chroma step, and finally, three most preferred black fabrics in each chroma level were selected for the next step. By this way, 21 black samples were selected, while some samples were selected as preferred blacks in both hue and chroma evaluation trials.

Lightness-based assessment (using rank-ordering method)

The third grouping of black fabrics was performed according to their lightness values which varied from 17 to 23 with 1-step interval. In this way, 7 different levels of lightness (level 1: 17 ≤ L* < 18, level 2: 18 ≤ L* < 19 ,and so on) were formed that included 6, 40, 60, 45, 40, 20, and 5 black samples. Then, samples were visually rank ordered from the minimum to maximum degree of blackness preference in each level and the average values of the assigned ranks were considered as the scale values of samples. Again, the three most preferred blacks in each level were selected according to the assigned values. Thus, 21 black fabrics were chosen as the most pleasing blacks from seven lightness levels for further evaluation.

Finding of the most preferred blacks of different groups (using rank-ordering method)

The collected samples from the hue, chroma, and lightness evaluation experiments were selected for the final evaluation. In fact, 12, 21, and 21 most pleasing blacks of previous sequence of experiments were chosen for further blackness evaluations. Due to the presence of identical samples within the groups, 42 black samples finally remained. In order to investigate the relationship between the blackness preference and the colorimetric properties of samples, black fabrics were visually assessed and rank ordered according to their blackness preference.

Running of pair comparison test on selected samples

To evaluate the validity of the results achieved from the rank-ordering methods, the dominance of blackness for a selected set of black samples was assessed by pair comparison test. According to the pair comparison method,[19–21] the numbers of pairs are calculated by equation (1):

$$\text{Number of assessments} = n(n-1)/2, \quad (1)$$

where n is the number of samples. Regarding equation (1), visual evaluation of 42 samples leads to 861 assessments for each observer which was very time-consuming procedure and practically impossible. Therefore, it was decided to select some black samples of different lightness and chroma values where they cover all of the four quadratic hue angles of CIELAB color ordering system to compare as pairs. In this way, samples related to each hue area were considered separately, and three black samples with different degrees of blackness preference were selected from each quadratic area without prior planning. Therefore, totally 12 black samples with different lightness, chroma and hue angles were semi-randomly selected out of the 42 rank-ordered black fabrics for the final visual assessments. According to the pair comparison technique, each sample was visually assessed with all other samples as pairs, and in each evaluation, the most preferred black was chosen.

Results and discussion

Rank-ordering method

Figure 3 shows the results of visual rank ordering of selected 42 most pleasing blacks. The horizontal axis represents samples' numbers. Samples are ordered from the lowest to the highest degree of blackness preference, and the vertical axis shows the assigned scale values. For example, sample #159 with the assigned scale value of 3 was perceived as the lowest pleasing black and sample #83 with the allotted scale value of 39.6 was felt as the most preferred black within the samples. Besides, the minimum and maximum of assigned ranks are shown by vertical lines for each sample. The results of rank ordering of 42 black fabrics as well as their colorimetric specifications are shown in Table 2.

According to Fig. 3 and Table 2, samples with the lowest and highest degree of blackness preference were evaluated more consistently by the observers than others. In other words, contrary to samples in the middle parts of Fig. 3, black samples in the two ends of the figure show lower standard deviation values. It means that, from the observers' point of view, making a decision about samples which benefited from the lowest or highest degrees of blackness preference was easier and more reliable than the others. In other words, observers did not have the same opinion on the blacks with medium degrees of blackness preference.

Figures 4, 5, and 6 show the relation between the colorimetric attributes, i.e., lightness, chroma, and hue angle of samples, and the assigned blackness values. According to Fig. 4, the blackness preference of samples increases with decreasing the lightness values for the samples with very low or very high scale values, which were perceived as least preferred or most preferred blacks. Besides, as shown in Fig. 4, there

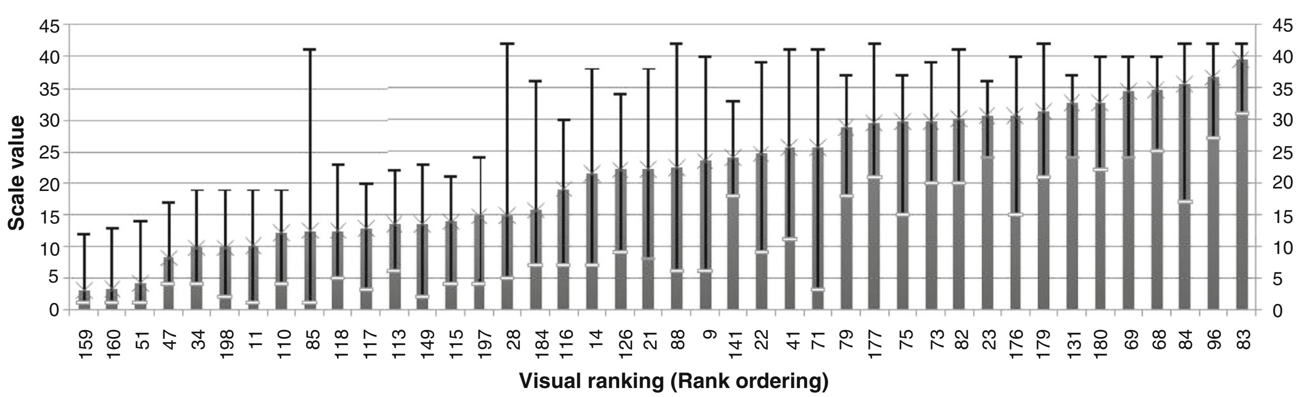

Fig. 3: Results of visual ranking of 42 black samples achieved from different groups

Table 2: Results of rank ordering of 42 black fabrics

Sample#	L*	a*	b*	C*	Hue angle	Scale value	Standard deviation
159	23.31	0.66	1.16	1.33	60.55	3	3.53
160	23.81	0.88	1.10	1.41	51.43	3.3	3.59
51	23.46	0.62	0.15	0.64	13.35	4.2	3.76
47	22.88	−1.59	0.38	1.64	166.66	8.2	4.10
34	22.00	0.02	0.05	0.05	72.93	9.8	5.65
198	19.29	−2.49	−0.37	2.51	188.51	9.8	5.35
11	19.61	−2.57	−0.64	2.64	194.02	10.1	5.99
110	18.08	1.46	−1.22	1.90	320.11	12.2	6.12
85	18.25	−3.35	−0.47	3.38	188.01	12.5	10.95
118	18.07	1.00	−0.94	1.37	316.77	12.5	5.25
117	17.99	1.32	−0.94	1.62	324.52	12.9	5.29
113	22.07	−2.15	1.25	2.49	149.85	13.6	6.11
149	19.09	−2.22	−0.07	2.23	181.82	13.6	6.65
115	18.03	1.05	−1.03	1.47	315.63	13.9	5.76
197	19.35	−2.04	−0.45	2.08	192.48	14.8	6.36
28	17.80	−2.60	−1.36	2.93	207.59	14.9	11.48
184	18.13	−2.95	−1.37	3.25	204.92	15.7	8.65
116	17.85	0.88	−0.90	1.26	314.35	19.1	6.19
14	21.80	0.20	−0.19	0.28	317.50	21.5	10.09
126	20.07	−0.33	0.42	0.53	128.13	22.1	7.37
21	21.29	−0.02	−0.30	0.30	265.44	22.2	9.59
88	17.65	−3.07	−0.55	3.12	190.11	22.4	11.65
9	20.79	−0.62	−0.57	0.84	222.50	23.5	10.34
141	19.48	0.14	0.76	0.77	79.86	24.1	4.84
22	21.34	0.17	−0.44	0.47	291.37	24.6	10.48
41	19.31	−1.59	−0.95	1.86	210.75	25.6	10.35
71	17.77	−2.13	−0.66	2.23	197.11	25.7	13.25
79	19.82	0.01	0.04	0.04	76.69	28.8	5.83
177	19.03	−0.40	0.34	0.53	139.49	29.5	6.52
75	19.73	0.15	0.05	0.16	17.05	29.7	6.20
73	20.15	−0.24	0.12	0.27	153.30	29.7	6.00
82	19.63	0.09	−0.10	0.13	312.34	30.2	5.90
23	19.05	0.03	−0.69	0.69	272.14	30.6	4.14
176	18.96	−0.67	0.24	0.71	160.39	30.7	7.99
179	19.04	−0.10	−0.03	0.11	194.22	31.4	7.31
131	18.62	−0.12	0.15	0.19	130.42	32.7	4.16
180	18.62	−0.30	−0.31	0.43	226.42	32.7	6.58
69	19.09	−0.60	−0.34	0.68	209.43	34.5	5.46
68	18.62	−0.12	−0.48	0.50	256.23	34.7	4.35
84	18.86	−0.13	−0.26	0.29	243.22	35.7	8.03
96	18.84	−0.83	−0.33	0.89	201.32	36.7	4.50
83	18.62	−0.03	−0.37	0.37	265.12	39.6	3.69

are some specimens that approximately benefit from same lightness values while they were assessed in different degrees of blackness. For example, samples #83, #68, and #180 with close lightness values of 18.62 were evaluated with different scale values of 39.6, 34.7, and 32.7, respectively. Hence, it could be concluded that the lightness does not solely affect the blackness preference of samples. On the other hand, samples with very close chroma values or hue angles provide the same effect. For instance, samples #84 and #73 with chroma values of 0.29 and 0.27 were averagely ranked as the 40th and 31st blacks, respectively, and similarly samples #34, #141, and #79 with the hue angle of 72.93°, 79.86°, and 76.69° are perceived as the 5th, 24th, and 28th black samples between the 42 available specimens, respectively. In other words, samples with the same lightness, chroma, or hue angles have not been evaluated as close specimens. It means that three different attributes of samples simultaneously affect the degree of preference of blackness. It is important to mention that samples #34 and #79, in addition to their very close hue angles, benefit from close chroma values (0.05 and 0.04, respectively) while they were ranked differently. In conformity with Table 2 and Figs. 4, 5,

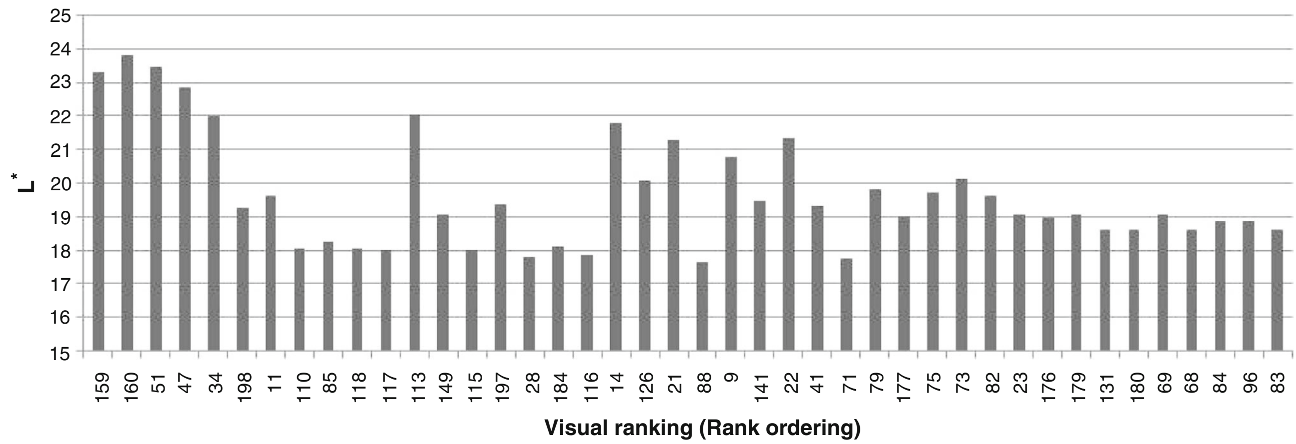

Fig. 4: The lightness values of rank-ordered black fabrics

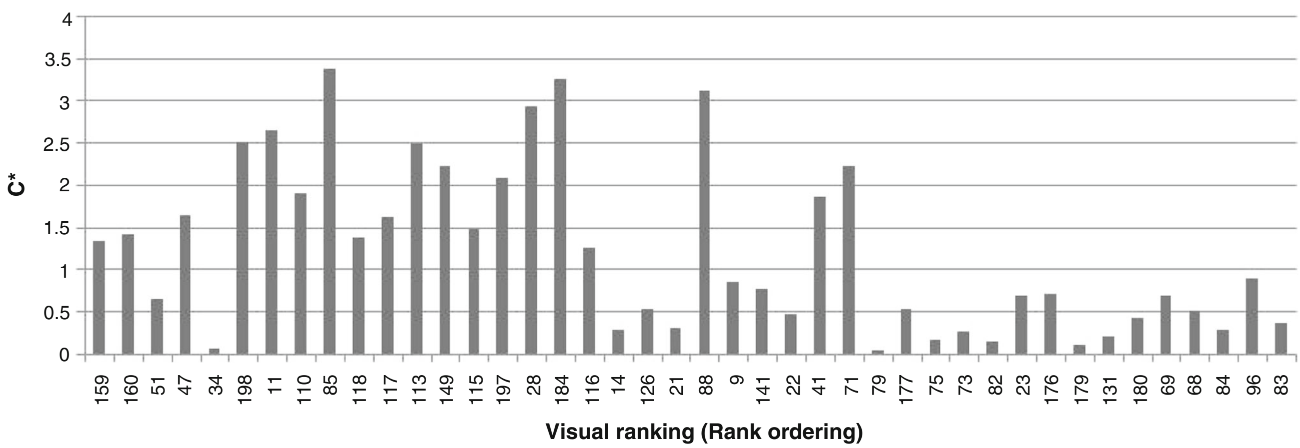

Fig. 5: The chroma values of rank-ordered black fabrics

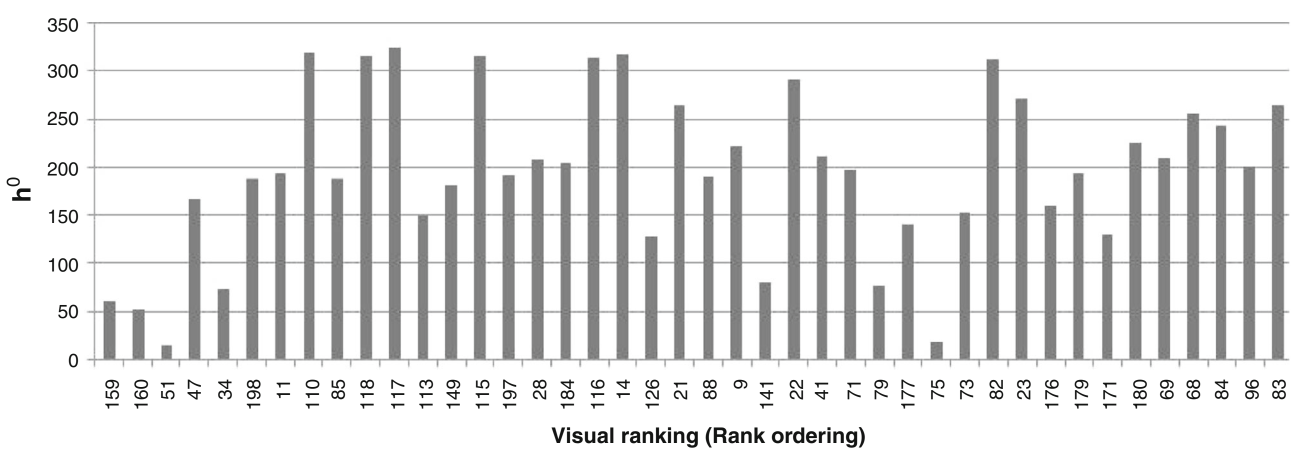

Fig. 6: The hue angles of rank-ordered black fabrics

and 6, it was found that the difference between the lightness values of the mentioned samples is the main source of difference between their scale values. In other words, samples with close hue and chroma values were ranked according to their lightness where the blackness preference increased with decreasing the lightness value. On the other hand, regarding the chroma values, samples #34 and #79 are approximately neutral blacks while they were not perceived as the most pleasant blacks among 42 black fabrics. It means that, while the chroma value plays an important role in the preference of blackness but in the available lightness range, the perfect black is not necessarily a neutral sample, i.e., those with chroma values of approximately zero.

Pair comparison method

From the Torgerson's hypothesis of normal distribution of designated ranks, the assigned ranks of 12 samples were averagely determined, and their interval properties were investigated. Figure 7 shows the assigned scale values of visually assessed black samples obtained from pair comparison evaluation trial. Moreover, the results of pair comparison of 12 samples in addition to their colorimetric specifications are presented in Table 3.

The results of the Chi-square method from the Mosteller test[22] showed that the interval property of numbers is not significant for the achieved scale values. It means that the orders of assigned ranks are only significant, and they simply represent the preference of blackness. For instance, sample #51 with the scale value of 0 is less pleasing black than sample #22 with the scale value of 0.80, or sample #83 with the scale value of 4.55 is the most preferred black among all 12 corresponding samples. Figures 8, 9, and 10 show the variation of lightness, chroma, and hue angles of evaluated paired samples, respectively. According to Fig. 8, the lightness of samples, except for samples #73, #79, and #84, decreases, while the blackness preference of them increases. Different behaviors are evident in Figs. 9 and 10 for chroma values or hue angles. Figure 10 shows that the most preferred black sample is positioned in the third quarter area of hue in the CIELAB color order system. In other words, blacks with bluish to cyanish tints were assigned as preferred samples by the majority of observers. From Figs. 8 and 9, it is found that in the lightness range of 18–23, sample #79 with the lightness value of 19.82 was not selected as the most preferred black while its chroma value is approximately zero. It means that, in addition to chroma value, the hue angle of samples plays an important role in the selection of preferred blacks.

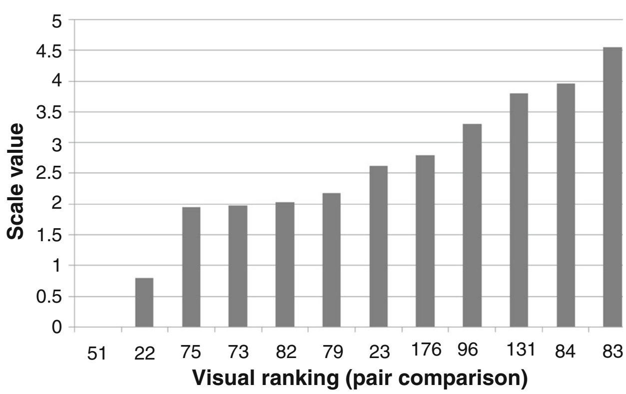

Fig. 7: Results of visual ranking of 12 black samples by the pair comparison method

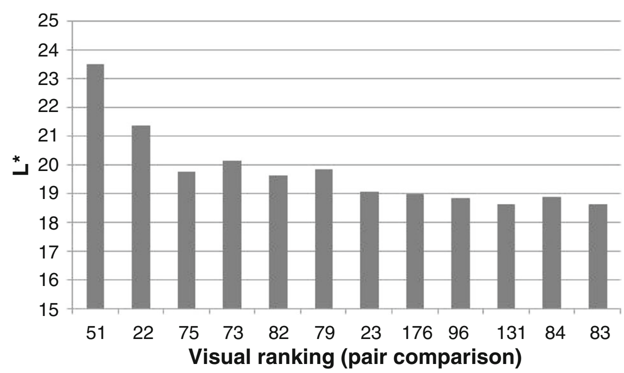

Fig. 8: The lightness values of rank-ordered black fabrics by the pair comparison method

Table 3: Results of visual ranking of 12 black fabrics by the pair comparison method

Sample#	L*	a*	b*	C*	Hue angle	Scale value
51	23.46	0.62	0.15	0.64	13.35	0
22	21.34	0.17	−0.44	0.47	291.37	0.80
75	19.73	0.15	0.05	0.16	17.05	1.95
73	20.15	−0.24	0.12	0.27	153.30	1.97
82	19.63	0.09	−0.10	0.13	312.34	2.03
79	19.82	0.01	0.04	0.04	76.69	2.16
23	19.05	0.03	−0.69	0.69	272.14	2.61
176	18.96	−0.67	0.24	0.71	160.39	2.79
96	18.84	−0.83	−0.33	0.89	201.32	3.30
131	18.62	−0.12	0.15	0.19	130.42	3.79
84	18.86	−0.13	−0.26	0.29	243.22	3.95
83	18.62	−0.03	−0.37	0.37	265.12	4.55

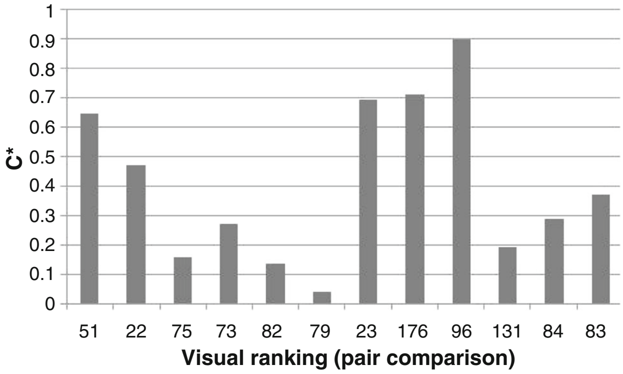

Fig. 9: The chroma values of rank-ordered black fabrics by the pair comparison method

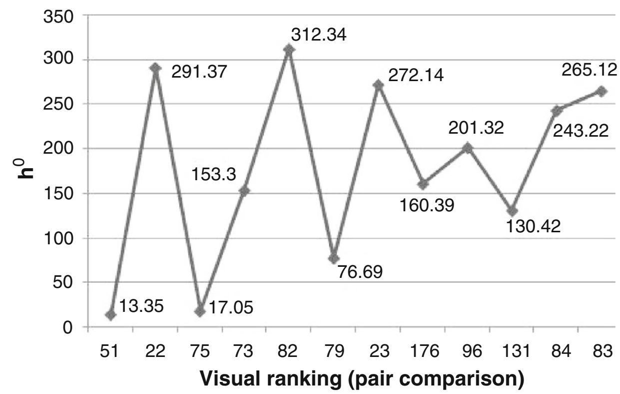

Fig. 10: The hue angles of rank-ordered black fabrics by the pair comparison method

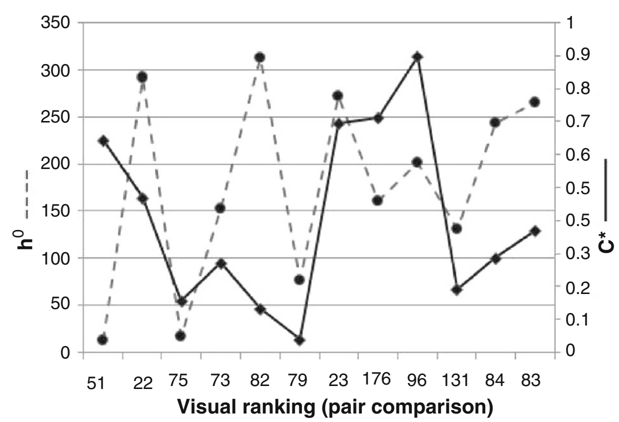

Fig. 11: The relationship between chroma and hue angles of rank-ordered black fabrics

Figure 11 shows the effects of two colorimetric factors: chroma and hue angle of black samples, simultaneously. The horizontal axis of Fig. 11 represents the visual order of samples according to their blackness preference. The left- and right-hand vertical axes of the figure show the hue angles and chroma values of samples, respectively. According to Fig. 11, irrespective of the chroma values, samples that approximately lay in the hue angles between 0° to 18° or around 300° were less preferred. In other words, observers evaluated the reddish black fabrics as samples with the lowest degree of blackness preference. The results related to the hue preference of observers in assessment of blackness are in conformity with the outcomes of Clonts et al.[5,9] that were reported on the basis of a limited number of the selected near-gray samples of Munsell chips. In fact, the results of the present work confirm the significant impact of hue on the visual assessment of black for a huge number of real black samples with various colorimetric attributes, i.e., different values of lightness, chroma, and hue. In comparison to Clonts and her coworkers' study,[9] the black samples benefited from different colorimetric properties and the observers evaluated the blackness of a very dense pack of blacks. The sparseness of near-black samples of Munsell chips that were used by Clonts et al.[9] could create a type of limitation in the visual evaluation sequence of samples by the observer that we attempted to avoid in this paper. Meanwhile, the latest work of Jafari et al.[10] showed that black surfaces could be spectrally described in a 3-dimensional space, and the results of the present work that focused on the colorimetric attributes of black samples reconfirm the previous finding. In other words, it seems that there are three important factors which affect the visual assessment of blacks similar to spectral property of them.

Observers' performance

The repeatability and reproducibility of results achieved from the pair comparison of 12 black samples were investigated to control the intraobserver and interobserver accuracy for visual assessments of blackness. In this way, the wrong decision criterion (WDC)[23–25] was used to investigate the observers' agreements for assigning ranks to the blacks among themselves (reproducibility) and in repeated visual assessments (repeatability).[26,27] Based on the WDC, if each observer's judgment was not in accord with the result achieved by all observers' assessments, one wrong decision was considered for her/him. Hence, the less WD% means the higher observers accuracy in blackness preference. The mean WD% of 12.8% was achieved for the interobserver accuracy while the values vary from the minimum value of 6.06% to the maximum value of 24.24%. Besides, the less mean WD% (11.45%) and standard deviation value (4.61) were achieved for females rather than males with the mean WD% of 14.14% and standard deviation of 5.02, which indicates the better agreement of women when evaluating blacks. On the other hand, the intraobserver variability was investigated by repeating the visual assessment of 12 black samples using the pair comparison method. In this way, 6 randomly selected observers including of 4 females and 2 males reiterated the visual experiments, and the WDC was used again to evaluate the results of 792 performed assessments. The values of 12.5%, 8.33%, and 18.18% were obtained for the mean, minimum, and the maximum of WD% that point out the high performance of observers in repeated visual assessments. Comparison of the results of observers' accuracy to those reported in literature[4,9] indicates the unanimity of observers for preference of blacks employed in this study. Obviously, this refers to the higher precision of pair comparison technique applied in this study rather than the rank-ordering method which was employed in those reports.

Evaluating the performance of suggested blackness indices

As an outcome of this study, the representation of a blackness index which operates on three colorimetric factors, i.e., lightness, chroma, and hue angle, would be necessary. Therefore, it seems that the blackness index that was suggested by Westland et al.[4] would probably assess the black samples better than those offered by Clonts et al.[5,9] The later indices are based on the one and/or two colorimetric parameters that could not possibly satisfy the effects of all colorimetric attributes on blackness.

In order to investigate the performance of the provided blackness indices, the correlation coefficients between the results of these indices and the results of visual assessment of 42 and 12 selected black samples were calculated. Table 4 shows the computed correlation coefficients as well as the proposed blackness indices obtained by suggested formulae. The conformation degree of provided blackness indices with the results of visual assessments is also shown in Figs. 12, 13, and 14, schematically. According to Table 4 and Fig. 12b, the Westland's index which is based on three colorimetric attributes, i.e., L*, a* and b*, provides the maximum correlation coefficient with the results of visual assessment of 12 black samples. On the other hand, regarding Table 4 and Figs. 13, 14, the low correlation coefficients were found between the results of visual evaluations of black samples and those suggested by Clonts and her coworkers that employed hue/hue-chroma attributes in the provided indices. Surely, the lack of lightness value in mentioned indices led to the weak assessment of blackness. It is noted that, contrary to the results of this investigation, these two later indices assigned less ranks to the blacker samples. As shown in Figs. 13a and 14, the negative slopes are seen in lines correlated the ranks achieved by the mentioned blackness indices and those from the visual assessments. In spite of small positive slope of Fig. 13b, it does not bring any particular value for the

Table 4: The performance of the suggested blackness indices for assessment of visually evaluated black samples

Blackness Index	Suggested by	Correlation coefficient	
		42 rank-ordered blacks	12 pair compared blacks
$B_3 = 8.6542 - 0.2583L^* - 0.0052a^{*2} + 0.0045b^{*2}$	Westland et al.[4]	0.199	0.814
Rank = 5.37 + 2.72 cosh°	Clonts et al.[9]	0.004	0.008
Rating = 3.60 + 1.27(C*) + 0.90cos(113.80-h°)	Clonts et al.[5]	0.215	0.015
$BI = 94.9926 - 3.2879L^* - 8.6402C^* - 5.8019\cos(h^c)$	Jafari et al.	0.796	0.738

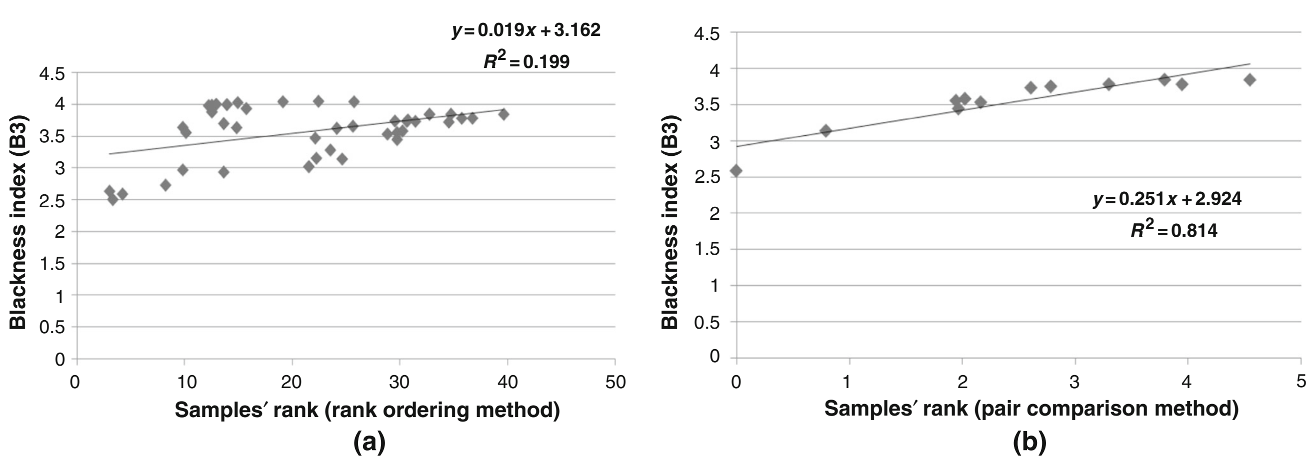

Fig. 12: The conformation of blackness index suggested by Westland et al. with the results of visual assessments of (a) 42 rank-ordered blacks and (b) 12 pair compared blacks

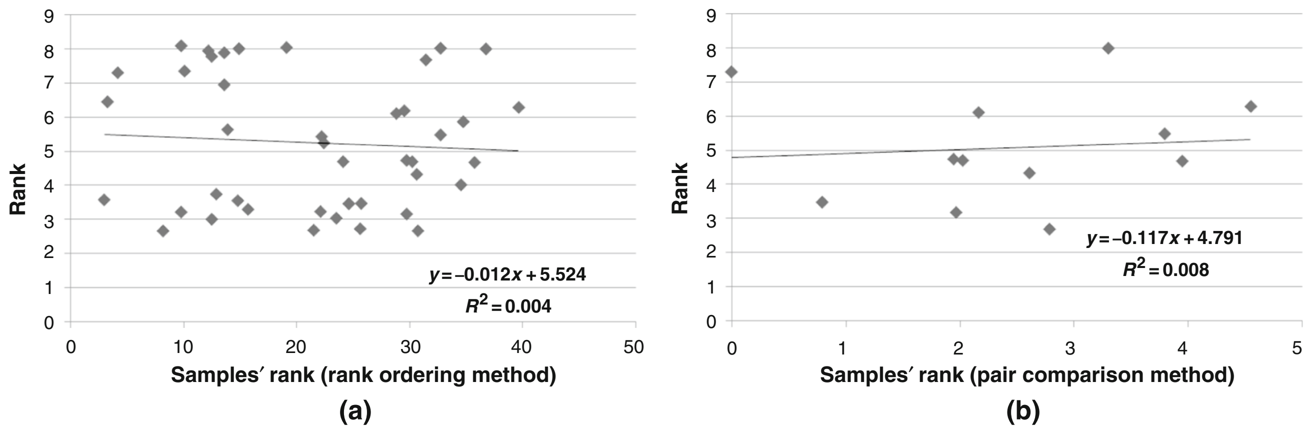

Fig. 13: The conformation of blackness index suggested by Clonts et al. based on the hue angle with the results of visual assessments of (a) 42 rank-ordered blacks and (b) 12 pair compared blacks

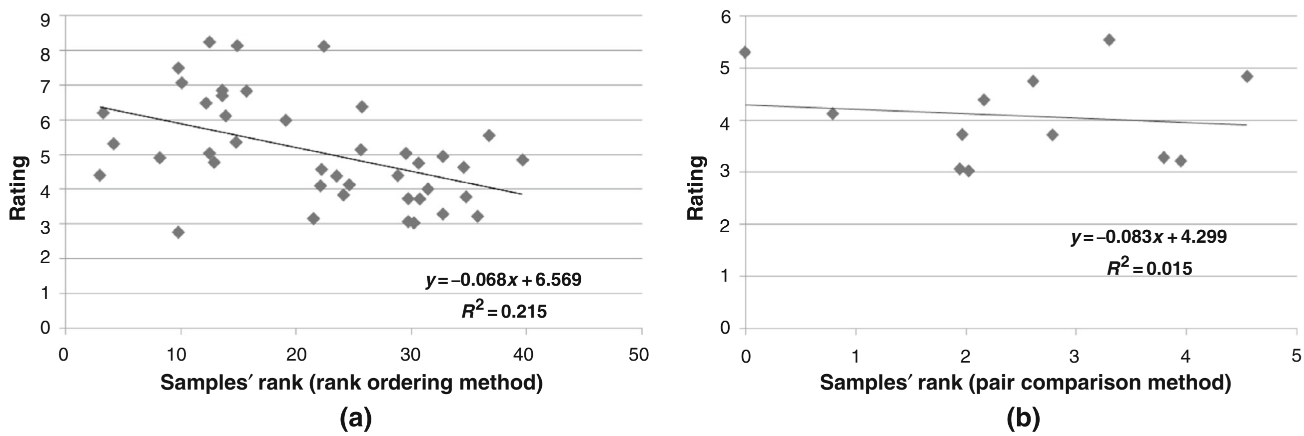

Fig. 14: The conformation of blackness index suggested by Clonts et al. based on chroma and hue angle with the results of visual assessments of (a) 42 rank-ordered blacks and (b) 12 pair compared blacks

evaluation of black samples. The second row of Table 4 shows that this blackness index only operates the hue angle, and the other colorimetric attributes, i.e., lightness and chroma values, are not considered. Besides, comparison of Figs. 12a and 12b as well as the results represented in Table 4 shows that the Westland's Blackness Index assesses the 12 black samples better than the 42 rank-ordered samples. This could probably be a result from higher precision of pair comparison technique than the rank-ordering method. Besides, the outcomes shown in Table 4 indicate the simultaneous effect of three colorimetric attributes, i.e., lightness, chroma and hue angle, as well as the significant role of lightness on blackness evaluation.

Finally, we attempted to propose a blackness index based on the results obtained from the visual ranking experiment of 42 black samples. Due to the importance of all colorimetric attributes of such samples, the devised index was designed in a manner that considers the lightness, chroma, and hue of samples. The proposed index that provided the best evidence to the observer results is shown in equation (2). As shown in the formula, the L*, C*, and the hue angle (in radian) play roles in developed index:

$$BI = 94.9926 - 3.2879L^* - 8.6402C^* - 5.8019\cos(h^c), \quad (2)$$

where superscript c denotes the hue angle in radians. Figure 15 shows the conformation degree of suggested blackness index with the results of visual evaluations, schematically. Besides, Table 4 represents the correlation coefficients between the proposed blackness index and the visual assessment results of 42 and 12 selected blacks. According to Fig. 15 and Table 4, the results of suggested blackness index is comparable with the results of visual evaluation of 42 samples by rank-ordering and 12 samples by pair comparison methods.

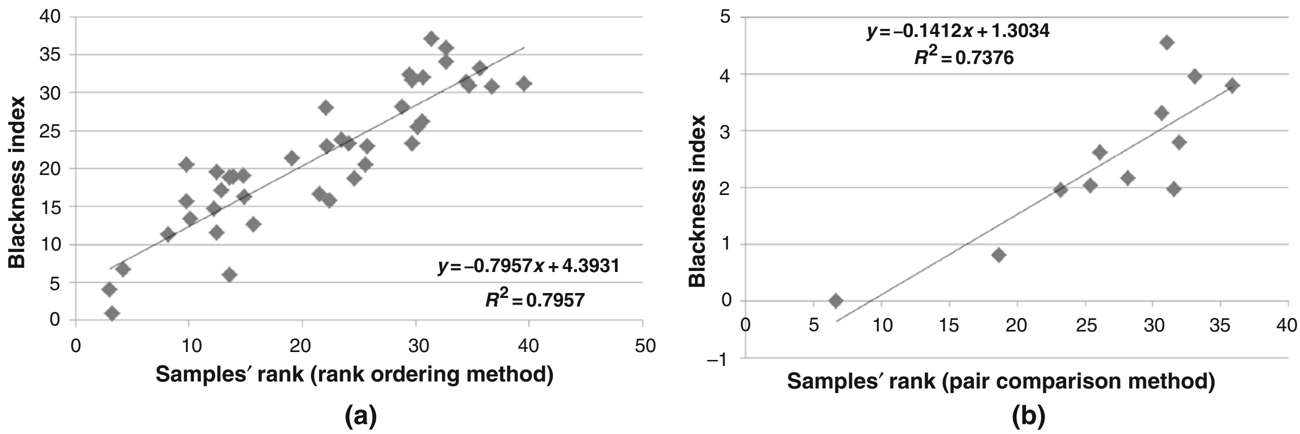

Fig. 15: The conformation of the suggested blackness index with the results of visual assessments of (a) 42 rank-ordered blacks and (b) 12 pair compared blacks

Conclusion

In order to determine the effects of colorimetric attributes on visual preference of blackness, 216 black coated samples in fabric form with great differences in their colorimetric attributes were prepared. Results of applying two different visual assessment techniques, i.e., rank-ordering and pair comparison methods, showed that all colorimetric attributes of sample including lightness, chroma, and hue angle simultaneously affect the preference of blackness. In the available range of lightness, the observers mostly preferred the bluish to cyanish blacks over the other hues. In fact, hue angle played a very important role in the selection of preferred black within the actual black samples that benefited from near-zero chroma values. In addition, for samples with approximately identical hue and chroma attributes, the blackness preference greatly increased with the decrease in the lightness values.

Finally, the conformation degree of suggested blackness indices with the results of visual assessments were compared, and it was found that the blackness index recommended by Westland et al. benefited from better correlation with the results achieved from pair comparison experiments. Meanwhile, a new blackness index was derived based on the visual evaluation results of the present work. It was found that the suggested blackness index shows a nearly good conformation with the results of visual evaluations.

Acknowledgments The authors thank the students of the Department of Textile Engineering of Isfahan University of Technology who participated in the visual assessment experiments of this study.

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