Effect of Colorimetric Attributes on Perceived Blackness of Materials

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Abstract

While black is one of the most prevalent industrial colors in the world, the colorimetric attributes of what is considered black vary significantly and the range of subtle hue undertones can be numerous. However, no systematic study can be found in the literature pertaining to the potential role of colorimetric attributes in the perceptual assessment of blackness. We have experimentally determined that the perception of blackness is influenced by hue and chroma using psychophysical assessments of a range of black materials.

In the initial part of this study a series of 2 × 2" precision cut glossy Munsell color samples comprising a hue circle with a lightness (L) of approximately 20.5 and chroma (C*) between 4 and 6 were assessed using thirty color normal observers and a filtered tungsten daylight simulator (D65). Observers were asked to arrange samples in order from most like black to least like black with no time limits in three separate sittings. In the second part of the study 27 over-dyed woolen samples were arranged in 2"× 3" dimensions. Samples in this set had a lightness range of 14-16 and C* of 0.5-3.5, and were assessed by 25 observers in two sittings in the same manner. The third set of samples comprised 24 precision cut 2" × 2" dyed acrylic samples with a L* range of 10.5-12 arranged around the hue circle. Samples were selected such that they comprised three concentric hue circles of eight evenly spaced samples each. The samples were divided into five sets according to chroma: A (C* = 0.12-0.20), B (C* = 0.42-0.57), C (C* = 0.89-0.97), D (C* = 1.58-1.86), and E (C* = 3.34-3.46). For the assessment of samples in the third set 100 color normal observers were employed that repeated the assessments in three separate sittings with at least 24 hours gap between each sitting. Analysis of the data indicates that, irrespective of chroma, on average samples with hue angles between approximately 200° and 270° were perceived to be the most black, i.e., cyan to bluish-blacks. Blacks with hue angles above 315° or below 45° (reddish-blacks) were considered to be the least black. Chroma and lightness also influenced the perceived blackness but for the majority of samples the effect was less pronounced.*

Introduction

The search of literature yields a very small number of manuscripts pertaining to the assessment of blackness. In 1980, W. D. Wright wrote a short article in *Die Farbe* on the perception of blackness in which he discussed the separation of television signals into a luminance channel and a chrominance channel [1]. To test whether this separation was valid, R.W.G. Hunt prepared a black-and-white slide and separated a chromatic slide of uniform luminance. Hunt and Wright found that combining the slides gave a reproduction of the original image, while the colors in the chromatic slide alone appeared garishly bright and unnatural. Wright discovered that the chromaticity was unchanged in the chromatic slide, and that the contrast provided by the luminance slide was critical to seeing the original image. Projecting the chromatic slide onto a uniform dark grey background did not return the colors to their original shades. From this, Wright drew a few conclusions. His first pertained to neural coding: current thinking at the time assumed that the black-white opponent channel was coded from the sum of the three types of cones in the retina. This idea led to the conclusion that blackness and luminance would be coded simultaneously, but his experiment showed that luminance must be separated from blackness at some point. His second conclusion was that the luminance alone was insufficient for color reproduction, as contrast is also important. Finally, he stated:

"*This raises the question of how we should measure or specify blackness. We might, perhaps, use the black-content scale of the Ostwald charts, or the black-white scale of the Natural Colour System, or the darkness-degree scale of the DIN System. What we do realize is that the blackness we are interested in is a subjective perception and not something that can be measured on any simple photometric scale. Moreover, the depth of the blackness that we perceive can be affected by quite small areas of contrasting lightness, for example, by the small highlights on the black grapes of Dr. Hunt's first demonstration slide.*"

To further the understanding of perceptual blackness a formal study was initiated at North Carolina State University in 2004 to examine the role of colorimetric attributes on the degree of blackness perceived. Concurrently, the study aimed to assess color vision various models pertaining to the perception of blackness. Preliminary results of the psychophysical assessments were presented in a special

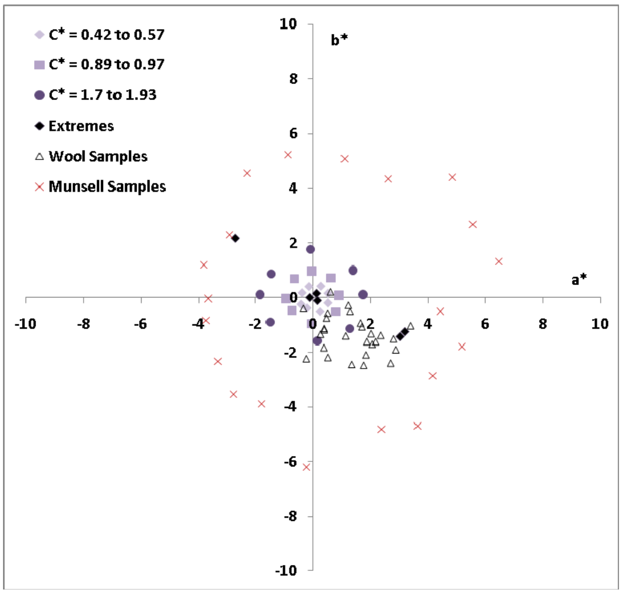

Figure 1. *Location of glossy Munsell, over-dyed wool and over-dyed acrylic samples used on the CIE a*b* plane.*

meeting of the ISCC in Portland, Oregon, USA [2]. In a different study in 2006 the preliminary results of work towards the development of a blackness index were reported [3]. This paper reports some of the additional results of the on-going endeavor at North Carolina State University.

Method

The location of all samples used in the study on the CIEa*b* plane is shown in Figure 1.

All observers who participated in this study were tested for having normal color vision using the Neitz test [4]. All samples were illuminated using a filtered tungsten daylight simulator (Macbeth SpectraLight III, X-Rite) calibrated to 6500K. All observers were adapted to the viewing conditions for at least two minutes.

In the first part of the study a range of low value, low chroma glossy Munsell samples that constituted a full hue circle were precision cut to 2” × 2” dimensions and mounted on PVC backings to facilitate observer handling during assessments. Samples had a L* range of 19.3-20.75 and C* of 3.66-6.58. For the assessments Munsell samples were divided into two groups as shown below:

- 5R, 5YR, 5Y, 5GY, 5G, 5BG, 5B, 5PB, 5P, 5RP and
- 10R, 10YR, 10Y, 10GY, 10G, 10BG, 10B, 10PB, 10P, and 10RP.

Due to the glossy nature of samples a chin rest was used during psychophysical assessments and samples were arranged such that the illumination/viewing geometry approximated 0/45 for all observers. This arrangement is shown in Figure 2.

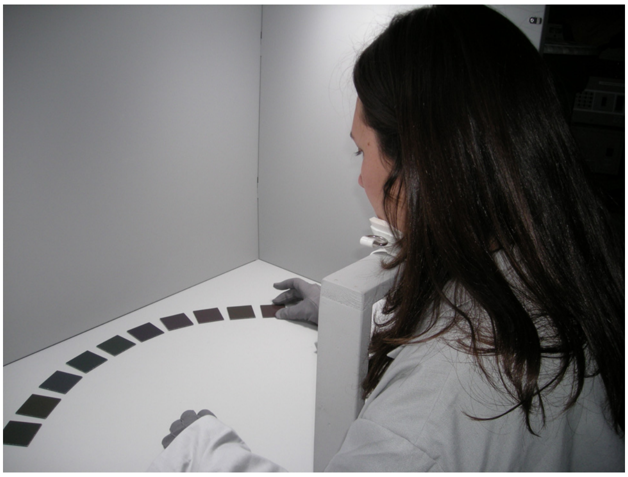

Figure 2. *Viewing Illumination geometry of glossy Munsell samples inside a SpectraLight III booth using simulated daylight (D65).*

The five most perceptually black samples ranked by each observer in each set were then exhibited to them as a new group to obtain the final ranks. Assessments were repeated twice with a time gap between assessments of at least 24 hours. The data thus collected were statistically analyzed.

In the second part of the study 45 wool samples were dyed to different hues within a color triangle. The colored wool samples were then over-dyed with C.I. Acid Black 194. Using a Datacolor SX600 spectrophotometer the colorimetric attributes of samples were determined using D65 illuminant and CIE 1964 Supplementary Standard Observer, specular and UV excluded and a large aperture. Samples were measured four separate times on four different locations to ensure uniformity and accuracy. Each sample was visually assessed and 27 out of the 45 dyed samples were chosen and separated into three groups of nine based on visual color variation and arranged based on their hue angle. Each sample was made into a 2” × 3” dimensions for easy handling. Each observer was asked to order four randomly presented sets of nine black samples from least black to most black. The three blackest samples from each set were set aside and used in the fourth set which was also assessed in the same manner. This test was administered to a different group of 25 color normal observers twice, each time on a different day.

Since samples representing the full hue circle could not be produced on over-dyed black wool samples in the third part of this study a large number of black samples were produced on an acrylic knit fabric. Two black cationic dyes at two concentrations were employed to initially dye the acrylic knitted fabric. The black fabric was then cut into smaller pieces and over-dyed with one of three concentrations of a trichromatic cationic dye mixture to produce twelve nominally black color triangles. From this set 30 precision cut 2” × 2” square samples with L* values between 10.5 and 12 were selected and mounted onto medium grey plastic backings. Twenty-four of these samples were selected such that they comprised three concentric hue circles of eight evenly spaced samples each with C* ranges of 0.42-0.57, 0.89-0.97, and 1.58-1.86. Six additional samples, with C* between either 0.12-0.20 or 3.34-3.46 were also used. The samples were divided into sets according to chroma: A (C* = 0.12-0.20), B (C* = 0.42-0.57), C (C* = 0.89-0.97), D (C* = 1.58-1.86), and E (C* = 3.34-3.46). The samples were mounted in a custom built display easel at a 45° angle and viewing was set normal to the plane of the display. One hundred color normal observers including fifty men and fifty women completed two tasks three times each on separate sittings and with at least 24 hour gap between assessments. In the first task, viewers were randomly presented with each of the thirty samples and each sample was categorized as either “black” or “not black.” In the second task, a reference black (an ‘ideal black’ that was essentially a light trap) was placed in the viewing booth and used to rate each sample on a custom scale as shown in Figure 3. The reference black comprised a wooden cube mounted at 45^o with a 2” square hole in the center of the plane facing the observer. The interior of the cube was lined with black velvet and the exterior was painted grey to approximately Munsell N7 to resemble the interior of the viewing booth. No light could escape the box.

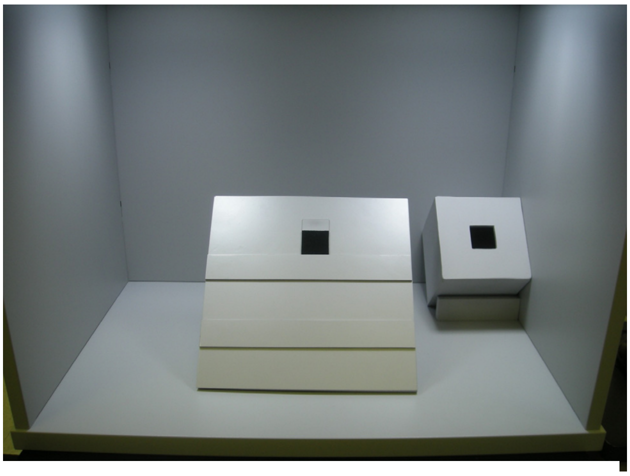

Figure 3. *Viewing Illumination geometry of acrylic samples against perfect black (the black light trap box to the right).*

All extraneous light was excluded during the assessments. Observers were asked to rate each of the thirty samples using a scale where the reference black was assigned a rating of 0. Observers were instructed that a rating of 10 should be given to what they consider as their borderline black sample and, consequently, that all samples that were not perceived as black should be rated 11 or higher. No endpoint was defined for the scale. Observers were allowed to respond with zero if they felt the sample matched the black reference box perfectly.

Results and Discussion

Due to the relatively high L* and C* values of Munsell samples the majority of observers did not consider these samples to be black. Observers were thus asked to rate samples in terms of most-like to least-like black. Results from this study were analyzed in terms of auto-concordance and concordance to determine inter and intra-observer variability in assessments. Results showed relatively high degrees of repeatability amongst observers with 81% calculated concordance. In addition the agreement among observers was also high with 76% calculated concordance. Results from this task were also analyzed in terms of hue angle associated with selections as shown in Figure 4.

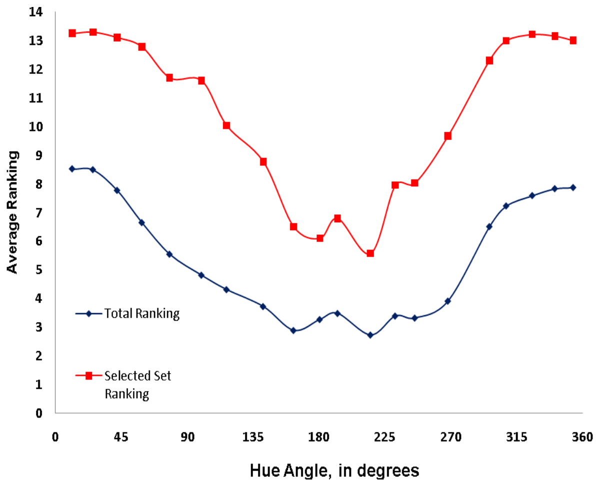

Figure 4. The effect of hue on perceived blackness of Munsell glossy samples for the total set and the blackest samples.

In order to address observer objections to Munsell samples' blackness, a range of over-dyed wool samples were produced and assessed by observers. The difficulty with these samples, however, was that a full hue circle could not be obtained via over-dyeing and the majority of over-dyed samples were purplish blacks with only a few in the blue-green region and none in the yellow or yellow-green region. Nevertheless since the chroma and lightness of these samples were significantly lower than those of glossy Munsell samples they were assessed by a group of observers twice to evaluate the potential role of chroma and lightness on perceived blackness. Results in terms of diminished blackness against hue angle are shown in Figure 5. Increased mean diminished blackness values indicate the sample is perceived as less black by the observer.

The number of over-dyed woolen samples which varied in hue across the visible range was insufficient and therefore conclusions on the potential role of hue on perceived blackness cannot be generalized. However, it can be seen that samples in the cyan to blue region were selected by observers as most black and those in the purple region were selected as being the least black. This was in agreement with the results of the Munsell sample set. In terms of lightness dyed samples had nearly constant values but their chroma varied between 0-4.

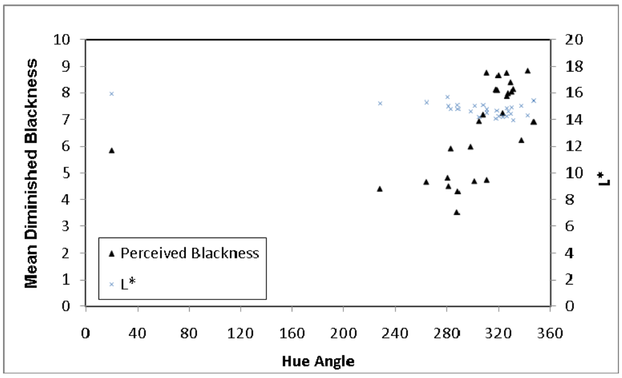

Figure 5. Relationship between perceived blackness against and hue angle of dyed samples.

While there were insufficient numbers of samples to assess the role of colorimetric attributes of dyed samples on their perceived blackness the potential role of variations in lightness and chroma on the perceived blackness were plotted as shown in Figure 6. The CIELAB color difference of samples against the most neutral black dyed sample were also separately calculated for the samples used in the study which are also shown in the figure. As can be seen there seems to be a direct relationship between increased chroma and diminished blackness which would seem expected. However, the correlation between increased chroma and diminished blackness is relatively weak ($R^2 = 0.54$). In terms of lightness the figure shows an inverse relationship, however, this trend is insignificant as determined by the weak correlation between parameters ($R^2 = 0.38$) and moreover the narrow range of lightness among these samples would make such comparisons inconclusive.

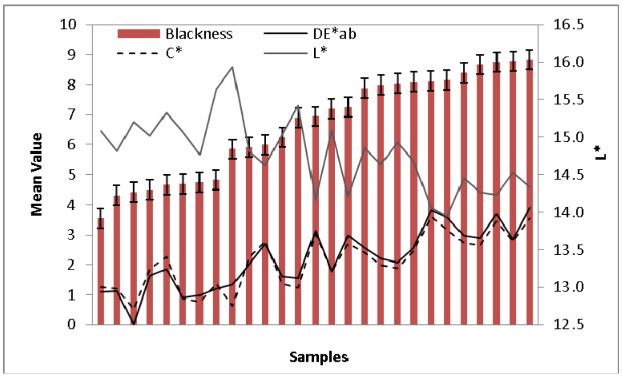

Figure 6. Mean blackness rank values including standard error as a function of ΔE^*_{ab} against standard (sample 3), C and L* of samples.*

Results from the third set of samples obtained by over-dyeing acrylic knitted fabric are separated into two tasks. The goal of task one was the elimination of all samples considered to be too distant from what would generally be considered black. This was analyzed using a binomial approach. Regardless of the response given during the first task all thirty samples were presented during the second task which rated the blackness of each sample against the reference black. A multivariate model was used to analyze the responses from the second task. The standard deviations of the mean rating given in the second task were also calculated, as were confidence intervals for the mean ratings. Finally, the results from the two tasks were compared, and the multivariate model for mean rating was tested against the results from the first observation trial. Excel software was used for the calculations of standard deviation and confidence intervals. A traditional t-test was used in this assessment, as the ratings of each sample were independent from each other. JMP software was used for the creation of the binomial and multivariate models.

It was decided to treat the first task as a separate experiment to help determine the boundaries of blackness in a given color space. Figure 7 shows the percent of observers identifying each sample black. The samples are divided by chroma group for clarity. Figure 7 also shows that higher chroma samples were considered black less often than samples of similar hue but lower chroma. It can also be seen that more observers agreed that samples were black when their hues were between 200° and 270°.

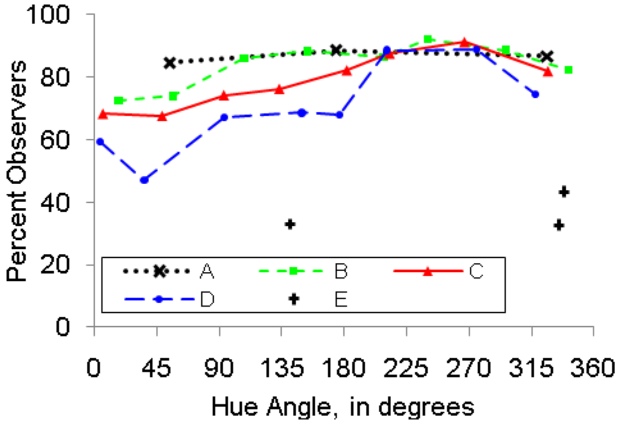

Figure 7, percent of observer considering each sample black as a function of sample's hue angle.

Task two enabled assessment of perceived blackness as a function of hue and chroma. Figure 8 shows a graph of blackness rating as a function of hue angle for chroma groups A-E. The lower the average blackness rating, the more black a sample is perceived. Again, the higher chroma samples were perceived to be less black than those with similar hues and lower chromas, and samples with cyanish hues were rated blacker than those with other hues, regardless of chroma.

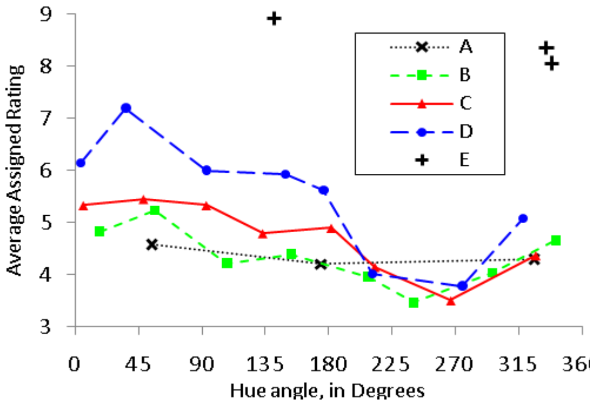

Figure 8. Mean perceived blackness ratings as a function of hue angle, h°, for chroma sets A-E.

The standard deviations for the mean ratings were also obtained during the second task. Observers agreed more with each other for the lower chroma samples, and more inter-observer variation was seen in the assessment of samples with increased chroma. Figures 9 and 10 show the standard deviation and the confidence intervals calculated for each mean rating respectively.

Two statistical models were obtained based on the results of this analysis. The first model gives the percent of observers who consider each sample to be black, while the second models the mean assigned rating of each sample. Both models are functions of the chroma (C*) and hue angle (h°). The correlation coefficients for these models are 0.86 and 0.87, respectively which are relatively high considering the psychophysical nature of the study.

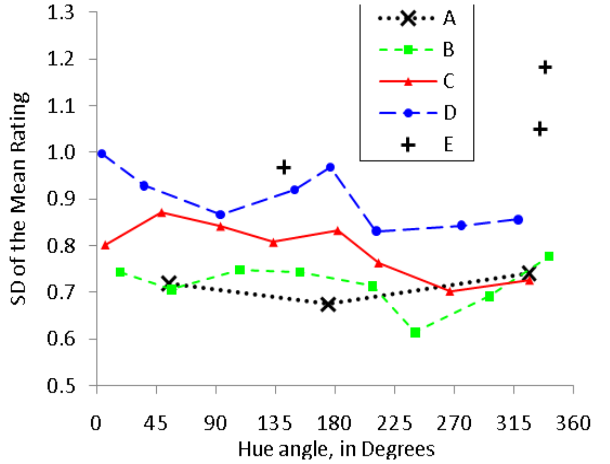

Figure 9. Standard deviations of mean assigned ratings as a function of hue angle.

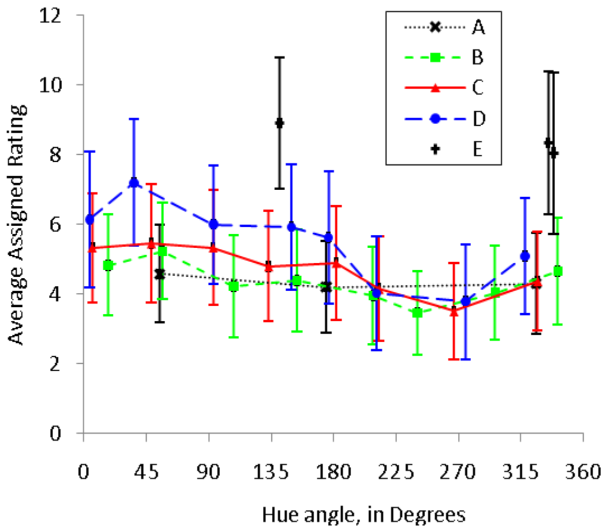

Figure 10. Confidence intervals for mean assigned ratings for each sample.

The models are shown in Equations 1 and 2. It should be noted that no lightness term is included in either model due to the limited range of variability in lightness of samples examined.

$$\%yes = 92.89 - 14.96(C^*) + 10.75\cos(165.22 - h) \quad (1)$$

$$Rating = 3.60 + 1.27(C^*) + 0.90\cos(113.80 - h) \quad (2).$$

Finally, the ratings model was used to predict ratings for the samples used in the first experiment. The model fits the data fairly well, indicating that the chroma effects are applicable to different sample types. Figure 11 shows how the predicted ratings agree with the empirical rankings. The predicted ratings have the same rough shape as the reported rankings, although the model seems to be less effective at hue angles in the purple region. It is interesting to note that some Munsell samples were assigned ratings below 10, indicating that they would be identified as black by the predictive model. This is not compatible with visual results. However, it is expected that the modification of the model to account for the increased variations in lightness and chroma values would resolve this inconsistency.

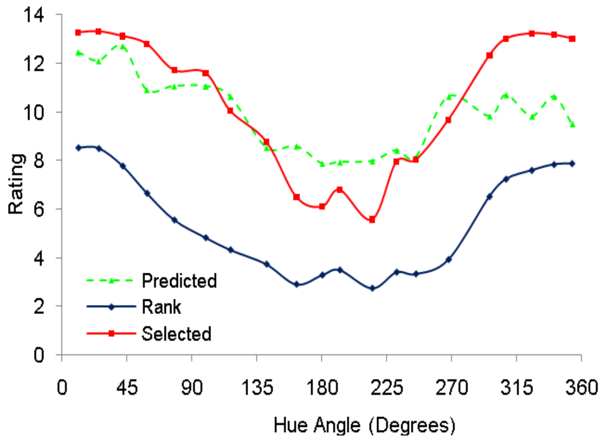

Figure 11. Modeled ratings for Munsell paper samples as a function of hue angle.

Conclusions

Analysis of the data indicates that, irrespective of chroma, on average samples with hue angles between approximately 200° and 270° were perceived to be the most black, i.e., cyan to bluish-blacks. Blacks with hue angles above 315° or below 45° (reddish-blacks) were considered to be the least black and the ratings trended between the most and least blacks as a function of hue angle. In general, the blackness rating was inversely proportional to C* for the samples that were not greenish- to bluish-black. Hence, for the observers studied, increasing C* has a deleterious effect on perception of blackness for all samples except greenish blacks and bluish blacks. This was in agreement with results obtained from glossy Munsell and over-dyed wool samples. Independent verification of the findings of this work should help color vision scientists in their modeling of achromatic channel as it seems that both perceived whiteness and blackness are increased with the introduction of bluish undertones.

Acknowledgments

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