Application of the Hunt94 Model to Color Perception of Outdoor Objects

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Abstract

Environmental laws mandate the protection of visibility conditions in national parks, and wilderness areas from atmospheric haze due to the emissions of anthropogenic air pollutants. To calculate the improvement in visibility that results from the reduction of these air pollutants, it is necessary to quantify the relationship of haze to the color appearance of objects being viewed through it. To this end, a field study was conducted in the Great Smoky Mountains National Park in eastern Tennessee. Color appearance of objects was quantified by color matching with a visual colorimeter. The Hunt94 color appearance model proved to be an invaluable tool that allowed color appearance of natural targets determined by an observer with a visual colorimeter to be compared to the color appearance predicted from the observed spectra of the target. The variable outside adapting conditions were quantified in terms of the model parameters by finding the values of the parameters that gave the best agreement between observer and spectrophotometer for a set of standard color cards. These model parameters were then applied to the natural targets. In this way, the differences between the adapting and observing conditions of the visual colorimeter and the natural outside environment could be reconciled. The apparent hue, colorfulness, and lightness of objects seen at a distance through haze are strongly dependent on perceived transparency of the atmosphere. The hue is approximately constant with changes in the optical depth of the haze. Lightness behaves similarly to hue. Colorfulness decreases exponentially with optical depth.

1. Introduction

This article discusses the manner in which the Hunt94 color appearance model[1] was utilized in a color matching experiment that was conducted to understand the perceptual effects of atmospheric haze on color appearance of objects. Although this research has applications in diverse fields such as transportation, machine vision, digital imaging etc., our interest was in improving current air quality-visibility models, which are used to evaluate the effect of changes in air pollution on atmospheric visibility. Protection of visibility has been an important issue since the Environmental Protection Agency promulgated the first visibility laws in 1977 and continues to be important due to the recent promulgation of a new regional haze rule that will place further emphasis on visibility protection. Current air quality-visibility models are based on the CIE XYZ color-matching system and the delta E-LUV color difference method. These systems may be reliably used in indoor color applications, but may not apply to the variable and uncontrolled outdoor viewing conditions.

2. Method

Rather than relying on laboratory studies of color perception or the CIE system, we have conducted field studies with on-site observers using a special outdoor colorimeter to quantify the color perception of objects. The outdoor colorimeter that was used for color matching was called the Visual Colorimeter for Atmospheric Research (VICAR) and consists of a small color monitor placed in an aluminum box.[2] A 2 degree color spot is generated against a white background, whose color appearance can be altered by means of a mouse and computer software. One eye views this color spot through an eyepiece, while the other eye views the object to be matched. The color matching is asymmetric in the sense that one eye is adapted to the high luminance and variable outdoor conditions, while the second eye is adapted to the low luminance, but constant VICAR conditions. At the same time that the color match was being made, the spectra of the targets were measured with a high-resolution telespectrophotometer. Six reference color cards and four natural targets were matched by each of the observers. The color cards were matched before and after matching the set of natural targets. In addition to serving as a reference (because of their proximity to the observers), the color card matches were used to derive optimal adapting conditions that served as inputs to the Hunt94 color appearance model, as discussed next.

One goal of the study was to develop a psychophysical model for natural targets that relates spectral measurements to colorimetric matches and the light attenuating properties of the atmosphere. Two problems need to be overcome; 1) to determine the unknown chromaticity of the outdoor adapting conditions, and 2) to transform from the variable, outdoor conditions to the constant, known adapting conditions of the VICAR. These problems were addressed by utilizing the Hunt94 color appearance model. A more detailed presentation of the approach can be found elsewhere.[3]

If the outdoor adapting conditions were known, the Hunt94 color appearance attributes of hue, colorfulness and brightness can be calculated, which should approximately equal those calculated from the VICAR color matches. Since the outdoor conditions are variable and unknown, non-linear optimization techniques were utilized for each color matching set to find the adapting conditions which resulted in the best fit between the hue, colorfulness and brightness derived from spectral measures and VICAR matches. After using the color cards to calculate the outdoor adapting conditions, spectral and perceived color appearance of the natural targets were calculated.

Color Appearance Modeling

Spectral measures of the color cards and natural targets were made under natural daylight conditions while the colorimeter matches were made under the adapting conditions of the VICAR. The three important differences in the adapting conditions between the VICAR and daylight are the chromaticity of the illuminant, the luminance level to which the eye is adapted, and the surround of the object. The screen on the CRT viewed in the VICAR is white except for the 2-degree color spot. At a color temperature of 9400K, the chromaticity of the screen is bluer than that of outside daylight. The screen luminance of the CRT is 150 cd/m2 while the luminance outdoors has an average in the thousands of cd/m2. A third difference is that the color monitor is placed in a dark enclosure inside the VICAR, so that the CRT screen is viewed in a dark surround. Before a comparison can be made between the color spot in the VICAR and the color coordinates derived from the spectra, corrections for the different adapting conditions are needed. The Hunt94 color appearance model provides these corrections.

The Hunt94 color appearance model for related colors was used. This is because the 2 degree color spot was viewed against a 15.8 x 21.6 degree white background. The inputs to the Hunt94 color appearance model are the CIE color coordinates of the object x and y and its luminance factor Y, along with values that describe the field in which the object is being viewed. The important parameters which describe the field are the reference white chromaticity (x_w,y_w), color temperature (CT), adapting luminance (L_a), chromatic (N_c) and brightness (N_b) surround induction factors and the chromatic (N_{cb}) and brightness (N_{bb}) background induction factors . It then outputs seven measures of color appearance defined as the hue (H), colorfulness (M), brightness (Q), saturation (s), chroma (c), lightness (J) and whiteness-blackness (Q_{wb}). An eighth parameter called the hue-composition (H_c) specifies the composition in terms of the four unique hues; blue, green, yellow and red. R. W. G. Hunt provides a detailed description of the Hunt94 model and its outputs in his book.[1]

The CIE coordinates of the objects in the vista can be derived from the spectral measurements. To compare the CIE coordinates derived from the spectra with those recorded by the colorimeter both are input to the Hunt94 model. The Hunt94 model was applied in the two color fields; the VICAR field V and the outside field O and on two groups of targets; the color cards and the natural targets. In the following a subscript of V will denote the VICAR field and O the outside field. Thus, L_{aV} is the adapting luminance of the VICAR and N_{bO} is the brightness surround induction factor for outside conditions.

The input parameters for the V field are all constant and known and predicting the color appearance of the color cards and natural targets in this field utilizing the Hunt94 model is straightforward. Table 1 shows the values of the adapting conditions for the V field. The values of the adapting luminance, color temperature and reference white shown for the V field are those of the white background in the CRT in the VICAR on which the 20 color spot is viewed. The x, y values for the illuminant, adapting field, background and proximal field are set equal to those of the reference white. The values of N_{cv} and N_{bv} were set equal to 1 and 25 as recommended by Hunt for CRT displays in dark surrounds.

Table 1. Hunt input constants for the VICAR field.

La_v	CT_v	N_{cV}	N_{bV}	x_{wV}	y_{wv}	Y_{wV}
150 cd/m^2	9500 K	1	25	0.3	0.315	100

The application of the Hunt94 model for the color cards and natural targets in the outside or O field is not so straightforward since the adapting daylight conditions are variable. The Hunt model parameters were estimated for each set of color matches. Luminance values in the O field were found to vary by up to a factor of 5. The values of the adapting luminance and color temperature for the O field are obtained from the measurements made by the spectrophotometer. The values of x_{wO} and y_{wO}, N_{cO}, N_{bO} are more difficult to obtain. Before the color appearance of objects in the O field can be calculated, optimal values of x_{wO} and y_{wO}, N_{cO}, N_{bO} must be estimated. These values are obtained from the color matching results of the color cards by employing an optimization procedure given below.

Calculating Optimized Hunt94 Parameters for the O Field.

A sensitivity analysis of the model indicates that hue H is very sensitive to changes in the reference white coordinates x_w, y_w. Similarly, values of colorfulness M and saturation s are sensitive to N_c while the brightmess and lightness values Q, J, c and Q_{wb} are sensitive to N_b. Thus, optimal values are estimated from the following non-linear least squares procedures:

Optimal values of the outside adapting white chromaticities x_{wO}, y_{wO} were obtained by minimizing the mean square difference between the hues of the color cards under the VICAR conditions, which are known, and the hues given by the Hunt94 model for outside conditions. The optimal value of the chromatic surround induction factor N_{cO} was obtained similarly by minimizing the mean square difference between the observed values of colorfulness M_v of the color cards and that predicted by the Hunt model for the outside conditions. Finally, the optimal value of the brightness surround induction factor N_{bO} is obtained by the same minimization as before expect that it is the lightness numbers that are being fit. All the calculations were made using an Excel spreadsheet version of the Hunt94 model and the minimization of the mean squared differences were done with the Solver nonlinear optimization function.

After the optimized values for x_{wO} and y_{wO}, N_{cO}, N_{bO} are obtained, the Hunt94 outputs for the natural targets in the O field (i.e. H_O, M_O, and J_O) can be obtained and the results can be compared with the results from the V field (H_V, M_V, and J_V).

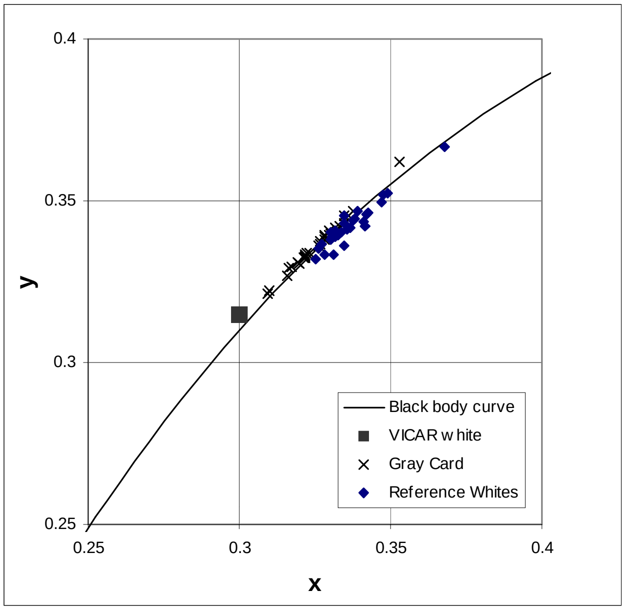

Figure 1. Chromaticity diagram of optimal reference whites for outside conditions as determined by observer SM.

3. Results

Results for Outside Reference White and Surround Induction Factors

Figure 1 is an x, y chromaticity diagram which shows the calculated optimal reference whites (x_{wO}, y_{wO}) for observer SM plotted in relation to the gray card measurements. The reference white points for daylight were obtained from the algorithm described in the last section. The average of the (x_{wO}, y_{wO}) values is (0.337,0.343). It is seen that this value is less bluish than that for the VICAR white (0.3, 0.315). For the sake of comparison the x, y values of the gray card measured by the spectrophotometer are also shown in the same graph. It is seen that there is moderately good agreement between the derived .reference whites and the measured gray card values. Overall, the average of the gray card values (0.326,0.337) is somewhat more bluish than the average of the reference whites. The results for observer SU are similar to observer SM.

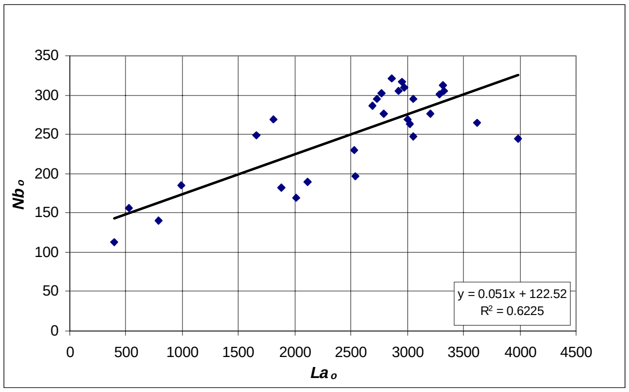

Figure 2. Plot of optimized outside brightness surround induction factor N_{bO} vs outside adapting luminance L_{aO} for observer SM.

Figure 2 is a plot of N_{bO} vs. L_{aO} for observer SM. It is seen that the optimized brightness surround induction factor increases linearly with the level of daylight adapting luminance with an r value of about 0.77. The average of the N_{bO} values is 211 (ranging from 113 to 306), larger than the value of 75 recommended by Hunt for "normal scenes". The average chromatic surround induction factor N_{cO} value obtained is 1.3 (ranging from 1.1 to 1.6). The results for N_{cO} and N_{bO} are similar for observer SU.

Results for Color Appearance of Color Cards

Table 2. Comparison of Mean Hunt94 Model Color Appearance Parameters for the Color Cards from Direct Matching Using a Visual Colorimeter (VICAR) and from Spectrophotometer Measurements Corrected to VICAR Conditions Using Optimized Hunt94 Model Parameters.

Card No.	Method	Hue	Colorfulness	Lightness
1	VICAR	96B 4G	15	39
	Spectroph.	95B 5G	16	41
2	VICAR	97B 3R	60	47
	Spectroph.	98B 2R	59	47
3	VICAR	87Y 13G	32	60
	Spectroph.	93Y 7G	41	57
4	VICAR	87G 13Y	29	58
	Spectroph.	89G 11Y	40	62
5	VICAR	60R 40B	31	56
	Spectroph.	60R 40B	34	55
6	VICAR	62B 38G	25	59
	Spectroph.	80B 20G	37	56

The average color appearance results for hue, colorfulness and brightness for the color cards are shown in Table 2. The values shown in the Table are the mean values of 29 measurements for observer SM. The results for 26 measurements by observer SU are similar. Hunt94 model results are given for two methods. The VICAR method gives the color appearance calculated using the chromaticities and Y determined by color matching with the visual colorimeter under conditions given in Table 1. The spectrophotometer method gives the color appearance determined by the spectaphotometer measurements of the color cards, using Hunt94 model parameters optimized to give as close an agreement between the two methods as possible. The results for the two methods should be the same if the Hunt model corrected perfectly for the differences in the conditions between the visual colorimeter and the variable outside conditions and the observers were perfect in their color matching. Clearly, the results were good enough to allow the use of the Hunt94 model parameters determined by the spectrophotometer method to be used with some confidence to calculate the color appearance of the natural targets under the visual colorimeter conditions. Thus making it possible to compare the color appearance as determined by the observer with the color appearance as determined by the spectrophotmeter, which was the main purpose of this study.

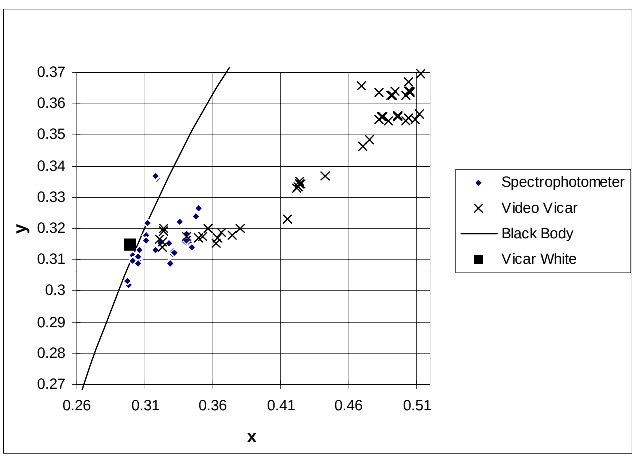

Figure 3. Chromaticities of the red barn determined by spectrophotometer and a visual colorimeter (Video Vicar)

Results for Natural Targets

Figure 3 shows chromaticity data for one of the natural targets, the rust-red roof of a barn about 3.5 km distant. The observer tended to see the barn as red even when the spectrophotometer indicated that the barn was nearly achromatic. In fact it was found that the color appearance of all the natural targets as determined by the observer with the visual colorimeter was not at all close to that as determined by the spectrophotometer measurements. This proved that the appearance of natural objects seen at a distance was affected by some factor not included in the Hunt94 model. This factor is the semi-transparent nature of the air through which the object is seen.

Due to transparency effects, the hue and brightness of objects perceived by the observer remain constant with changes in the optical depth. This is because the hue and brightness of the path radiance are perceptually discounted by the observer while perceiving the object. Path radiance is the radiance that is scattered into the line of sight by fine particles present in the atmosphere. Path radiance is predominantly blue because the fine particles enrich shorter wavelengths and it has a strong component from skylight. On the other hand, spectral hue as determined by the spectorphotometer varies depending on the amount of path radiance. At large optical depths (dense haze), the spectral hue approaches blue. At small optical depths (light haze), the spectral hue equals the perceived hue because of the lack of a transparency effect. In brightness perception, the brightness of the path radiance is discounted, while perceiving the brightness of the object. Spectral brightness is the sum of the brightness of the haze layer and brightness of the object, so perceived brightness is always smaller than, or at most equal to spectral brightness.[4] Perceived colorfulness is the only attribute that changes as haze changes, and it decreases exponentially with optical depth.[5]

4. Conclusions

The Hunt94 color appearance model proved to be an invaluable tool that allowed color appearance of natural targets determined by an observer with a visual colorimeter to be compared to the color appearance predicted from the observed spectra of the target. The variable outside adapting conditions were quantified in terms of the model parameters by finding the values of the parameters that gave the best agreement between observer and spectrophotometer for a set of standard color cards. These model parameters were then applied to the natural targets. In this way, the differences between the adapting and observing conditions of the visual colorimeter and the natural outside environment could be reconciled. Although the Hunt94 model proved to be well suited to this rather unusual application, other more recent color appearance models such as CIECAMS97s should prove just as serviceable. However, the Hunt94 model is particularly well suited to this application because the adjustable parameters are related to the hue, colorfulness, and lightness in a way that makes it relatively easy to optimize the parameters.

Although not the main subject of this paper, understanding the color appearance of natural objects seen through atmospheric haze was the driving force of this work. This study found that apparent hue, colorfulness, and lightness of objects seen at a distance through haze are strongly dependent on perceived transparency of the atmosphere. The hue is approximately constant with changes in the optical depth of the haze. Lightness behaves similarly to hue, and colorfulness decreases exponentially with optical depth.

5. References

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5. Ronald C. Henry *et al.*, submitted to *J. Opt. Soc. A.*