Sources and Surfaces - Evaluating Spectral Distribution Interactions Using Roadway Signage

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Introduction

Visual tasks vary greatly, from detection of motion in the visual periphery to discerning details in foveal tasks, such as reading. The human visual system employs different photoreceptors and nerve processes depending on the position of the task on the retina, and for foveal tasks utilizes color vision. There is a benefit in the use of spectral information that presents additional dimensions in which to evaluate differences, or contrast. With monochromatic vision, only luminance differences are visible, but with color vision, there are color differences to be detected.

Historically the colors in view were lower in saturation than many that are available to us today[1]. The development of technology in dyes, pigments and chemistry has greatly expanded the range of available colors. Furthermore the development of sources with non-continuous spectral power distributions - such as high pressure sodium, fluorescent and metal halide - has created interactions between sources and surfaces which were not even possible when the currently accepted method of evaluating contrast was developed and adopted.

For foveal tasks, the goal of any lighting system is to produce color difference. Color difference threshold is defined in the 'Glossary of Lighting Terminology'[2] as "the difference in chromaticity or luminance between two colors that makes them just perceptibly different. The difference may be in hue, saturation, brightness (lightness for surface colors) or a combination of the three". Color difference is what we perceive, without color difference there is no edge definition, without edge definition shapes are not discernible. Color difference incorporates both chromaticity difference and luminance difference. Color difference calculations are very rarely performed because they are based on spectral information not contained in the lumen, which is used for conventional evaluations of lighting systems.

In the 'Glossary of Lighting Terminology'[2], 'contrast' is defined as 'luminance contrast'. Presently only luminance difference or contrast is typically calculated and chromaticity differences are ignored. Two alternative equations for luminance contrast are[2]:

Eq 1: $C = (L_{max} – L_{min}) / L_{max}$

Eq 2: $C_{mod} = (L_{max} - L_{min}) / (L_{max} + L_{min})$

According to the current method of calculating luminous contrast, a red surface and a green surface having the same luminance placed side by side are indistinguishable - the boundary of the two surfaces should not be discernible. Experience shows this is not true. The boundary will be discernible because the two surfaces interact with the incident luminous radiation in different ways, producing differences in the reflected radiation that the eye can discern. A surface is visually interpreted as yellow because that surface is reflecting a combination of wavelengths of the incident radiation that produce a stimulus in the eye that is interpreted as yellow. If the incident radiation does not contain wavelengths of radiation to produce a sufficient yellow stimulus, the surface's appearance will lose some or all of its color.

This work reports the changes in reflectance when different surfaces are evaluated using a spectrally informative methodology. Since the integration of the spectral power distribution with the spectral luminous efficiency function is commutative, the integration can be performed anywhere along the mathematical process of calculating luminance. By commuting the integration from the first step in the process to the last step and carrying spectral radiant energy data (watts at a given wavelength) through the calculation, the results provides a more accurate representation of the 'brightness' of a surface because the interaction of spectral radiance and spectral reflectance are incorporated into the calculation. Differences in reflectance values demonstrate the significance of this method.

The attention to roadway signage arises from that visual task's foveal nature, consistency, frequency, and significance. Furthermore the use of highly saturated colors for conveying information (e.g. Stop) and the likelihood of illumination by non-continuous sources means reading roadway signage is a visual task that is particularly well suited to evaluation by a spectrally-informed methodology.

Procedure

The calculations are mostly a series of one-dimensional vector multiplications followed by a summation along the resulting vector. The luminous reflectance for a surface is calculated for a specific source by determining the luminous flux off the surface and dividing that value by the luminous flux onto the surface from the source.

The calculation of the luminous flux from a source combines the source or surface radiative intensity and a spectral luminous efficiency function. The equation for the luminous flux of a source with radiant power distribution S(λ) evaluated for spectral sensitivity by any v(λ) function is[2,3]:

Eq 3: $\text{Lumens}_{\text{source}} = K * \sum [S(\lambda) * v(\lambda)]$

The luminous flux off a surface is calculated by multiplying together the source radiant power distribution S(λ), the surface radiative reflectivity p(λ) and the spectral luminous efficiency function v(λ) at each wavelength and then summing over the spectrum and multiplying that sum by constant K where K is a constant for either the photopic (K = 683) or the scotopic (K = 1700) spectral luminous efficiency function[2,3].

Eq 4: $\text{Lumens}_{\text{surface}} = K * \sum [S(\lambda) * p(\lambda) * v(\lambda)]$

The summations are made over the range of 360 to 770 nanometers. In accordance with the foveal visual task being considered here, all of the calculations use the "photopic visual sensitivity function" and the corresponding value for K = 683.

Fifteen different sources are used throughout the calculations. These sources are: an equal energy source with constant radiant power across the spectrum (EqE); CIE D65[4] (C_D); CIE Illuminant A[4] (C_A); 100 watt High Pressure Sodium (H10); 150 watt High Pressure Sodium (H15); 250 watt High Pressure Sodium (H25); 400 watt High Pressure Sodium (H40); 250 watt horizontal Metal Halide (M2h); 250 watt universal Metal Halide (M2u); 400 watt horizontal Metal Halide (M4h); 400 watt universal Metal Halide (M4u); 3000K Fluorescent (F30); 3500K Fluorescent (F35); 4100K Fluorescent (F41); and 6500K Fluorescent (F65). The Fluorescent, HPS and MH sources' spectral power distribution data used in this work were supplied by Phillips Lighting. All data for sources were provided in single nanometer bandwidths.

Sign spectral reflectance data for three series of signing film was provided by 3M. 3M provided sign color reflectivity profiles for Blue, Green, Yellow, Orange, Red, Brown, and White. The provided data was obtained using a Hunter Labscan colorimeter using 45/0 incident radiation / receptor angles for a 2 degree observer. The data was provided in 10nm bandwidths and linearly expanded to single nanometer bandwidths. Each of these reflectance profiles is evaluated under each of the sources in the set.

A Black spectral reflectance profile was also developed by establishing 2.0% reflectance over the entire spectrum, in accordance with the FHWA requirements for black sign color[5].

Calculations for reflectance and luminous contrast were performed and the results presented below. Color calculations were also made for all the surfaces under all the illuminants using the CIE LAB procedure[2,3,6]. This procedure provides results that represent loci in a three dimensional color space. CIE LAB also provides the lightness index of the surface as L*. The 'Glossary of Lighting Terminology'[1] defines lightness as "the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting". In the CIE LAB procedure, each source's absolute white is defined as L* = 100.

The 'Glossary of Lighting Terminology'[1] defines CIE (L*, a*, b*) uniform color space (CIELAB) as "a transformation of CIE tristimulus values X, Y, Z into three coordinates that define a space in which equal distances are more nearly representative of equal magnitudes of perceived color difference. This space is specially useful in cases of colorant mixtures".

The distances between L*a*b* loci (delLAB) correspond to the magnitude of the color difference between the two colors or sources as perceived by the human visual system. This distance delLAB is calculated as a typical three-dimensional distance, the square root of the sum of the squared differences[2,3,6]. The use of the delLAB Euclidean distance can be justified as it is the same type of distance that has been used by the lighting industry since 1976 for the calculation of Color Rendering Indices[7].

Eq 5: $\text{delLAB} = [(L^*_1 - L^*_2)^2 + (a^*_1 - a^*_2)^2 + (b^*_1 - b^*_2)^2]^{0.5}$

For the purposes of these calculations, the radiant power distribution of each source was scaled to 100 lumens. All calculations of luminous quantities were performed using the CIE photopic sensitivity curve (y bar 2).

Results

Table 1 shows the typical color information about the fifteen different sources. The Correlated Color Temperatures (CCT) and Color Rendering Indices (CRI) reported in the above table were calculated in compliance with procedure established by the CIE[2,3,6,7]. There is a wide range in the 'color rendering properties' of the sources used in this work.

Table 1: Sources' Data

Source	Abbr.	x	y	CCT	CRI
Equal Energy	EqE	0.33	0.33	5455	95
CIE D65	C_D	0.31	0.33	6502	100
CIE Illuminant A	C_A	0.45	0.41	2856	100
HPS 100W	H10	0.52	0.42	2060	16
HPS 150W	H15	0.51	0.42	2174	21
HPS 250W	H25	0.52	0.41	2001	21
HPS 400W	H40	0.52	0.42	2116	16
MH 250W Horiz	M2h	0.39	0.40	4002	64
MH 250W Univ	M2u	0.38	0.40	4061	53
MH 400W Horiz	M4h	0.37	0.39	4319	68
MH 400W Univ	M4u	0.40	0.40	3776	58
Fluorescent 3000K	F30	0.44	0.41	2919	85
Fluorescent 3500K	F35	0.42	0.40	3326	87
Fluorescent 4100K	F41	0.39	0.38	3813	87
Fluorescent 6500K	F65	0.32	0.34	6088	87

Table 2 shows the chromaticity coordinates under CIE D65 and CIE Illuminant A for the different colors. These values are in compliance with the FHWA requirements for these sign colors for day and night[5].

Table 2: Sign Film Chromaticity Coordinates

		CIE D65		CIE Illuminant A	
		x	y	x	y
White	ENG	0.32	0.34	0.45	0.41
	HIS	0.31	0.33	0.44	0.41
	VIP	0.31	0.33	0.44	0.41
Blue	ENG	0.14	0.11	0.16	0.18
	HIS	0.14	0.13	0.15	0.22
	VIP	0.15	0.13	0.16	0.24
Green	ENG	0.14	0.42	0.18	0.51
	HIS	0.14	0.44	0.17	0.53
	VIP	0.13	0.42	0.17	0.51
Yellow	ENG	0.50	0.48	0.55	0.44
	HIS	0.52	0.47	0.57	0.43
	VIP	0.53	0.47	0.57	0.43
Orange	ENG	0.58	0.40	0.61	0.39
	HIS	0.54	0.40	0.60	0.39
Red	ENG	0.66	0.33	0.68	0.32
	HIS	0.66	0.32	0.68	0.32
	VIP	0.66	0.32	0.68	0.32
Brown	ENG	0.52	0.40	0.59	0.39
	HIS	0.50	0.40	0.58	0.39

Table 3 shows the calculated reflectance for the different colors under each source. Values are shown with two digits. This is to show the numerical basis for values calculated below, and not as an indicator of the precision of the results. In general the values should be considered as having accuracy corresponding to one significant digit, consistent with the variability of photometric data across the industry. Where these values are used in further calculations, all intermediate digits are carried forward for those calculations.

Table 4 shows the L*, a* and b* values for each of the sign films for each of the illuminants.

Table 3: Sign Film Reflectances

		EqE	C_D	C_A	H10	H15	H25	H40	M2h	M2u	M4h	M4u	F30	F35	F41	F65
White	ENG	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%	45%
	HIS	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%	33%
	VIP	41%	42%	41%	41%	41%	41%	41%	41%	41%	41%	41%	41%	41%	41%	42%
Blue	ENG	2.4%	2.6%	1.5%	0.7%	0.8%	0.8%	0.8%	1.8%	1.5%	1.9%	1.6%	1.1%	1.3%	1.5%	2.1%
	HIS	3.3%	3.5%	2.2%	0.8%	0.9%	0.8%	0.9%	2.4%	2.2%	2.6%	2.2%	1.8%	2.1%	2.3%	3.1%
	VIP	1.9%	2.1%	1.3%	0.5%	0.6%	0.5%	0.6%	1.5%	1.4%	1.6%	1.3%	1.2%	1.4%	1.5%	1.9%
Green	ENG	5.5%	5.9%	4.1%	1.6%	1.7%	1.6%	1.6%	4.4%	4.0%	4.7%	4.0%	3.8%	4.1%	4.5%	5.5%
	HIS	6.2%	6.6%	4.6%	1.5%	1.7%	1.6%	1.6%	4.9%	4.4%	5.2%	4.4%	4.5%	4.9%	5.3%	6.5%
	VIP	5.6%	6.0%	4.2%	1.6%	1.7%	1.6%	1.6%	4.5%	4.0%	4.8%	4.0%	3.8%	4.2%	4.5%	5.6%
Yellow	ENG	37%	35%	41%	48%	48%	48%	48%	40%	42%	40%	41%	42%	41%	40%	37%
	HIS	18%	17%	21%	25%	25%	25%	25%	20%	21%	20%	21%	21%	20%	20%	18%
	VIP	26%	25%	30%	37%	37%	37%	37%	30%	31%	29%	31%	30%	29%	28%	26%
Orange	ENG	25%	23%	31%	44%	43%	44%	44%	30%	31%	29%	31%	28%	26%	25%	20%
	HIS	17%	16%	20%	26%	25%	26%	26%	19%	19%	18%	20%	20%	19%	18%	16%
Red	ENG	6.1%	5.4%	8.5%	7.8%	7.4%	8.3%	7.5%	5.1%	4.5%	5.0%	5.1%	8.4%	7.7%	7.1%	5.5%
	HIS	4.2%	3.7%	5.8%	5.7%	5.4%	6.1%	5.5%	3.7%	3.3%	3.6%	3.7%	5.7%	5.3%	4.8%	3.7%
	VIP	6.7%	5.9%	9.5%	8.8%	8.4%	9.5%	8.5%	5.5%	4.8%	5.4%	5.5%	9.8%	9.0%	8.3%	6.3%
Brown	ENG	5.8%	5.5%	6.9%	7.5%	7.3%	7.6%	7.4%	6.0%	5.9%	5.9%	6.1%	7.2%	6.9%	6.6%	5.9%
	HIS	4.5%	4.3%	5.3%	6.3%	6.1%	6.3%	6.2%	4.9%	5.0%	4.8%	5.0%	5.0%	4.8%	4.7%	4.2%

Table 4: CIE LAB Coordinates for Sign Colors

		EqE			C_D			C_A			H10			H15			H25			H40			[continued]
		L	A	B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	B	
Whi	ENG	73	-3	5	73	-3	4	73	-2	4	73	-1	4	73	-1	4	73	-1	4	73	-1	4	
	HIS	64	-2	-1	64	-2	-1	64	-2	-1	64	-1	-1	64	-1	-1	64	-1	-2	64	-1	-1	
	VIP	70	-2	-2	71	-2	-2	70	-2	-3	70	-1	-3	70	-1	-3	70	-1	-3	70	-1	-3	
Blu	ENG	17	12	-51	19	15	-50	13	-8	-60	7	-2	-71	7	-3	-70	7	-2	-71	7	-3	-70	
	HIS	21	5	-49	22	8	-48	16	-21	-56	7	-7	-73	8	-8	-71	7	-7	-72	8	-8	-72	
	VIP	15	6	-40	16	8	-38	12	-18	-44	5	-4	-56	5	-5	-55	5	-4	-56	5	-4	-56	
Grn	ENG	28	-59	0	29	-59	1	24	-55	-14	13	-25	-30	14	-26	-29	13	-25	-30	14	-26	-30	
	HIS	30	-64	3	31	-63	3	26	-61	-12	13	-29	-31	14	-31	-30	13	-30	-30	13	-30	-30	
	VIP	28	-61	0	29	-61	1	24	-57	-14	13	-27	-31	14	-28	-30	13	-27	-30	13	-28	-30	
Yel	ENG	67	11	97	66	11	95	70	16	96	75	3	105	75	3	104	75	3	105	75	3	105	
	HIS	50	15	83	49	15	81	53	18	84	57	5	92	57	5	91	57	5	92	57	5	92	
	VIP	58	18	95	57	18	94	62	22	97	67	5	105	67	6	104	67	5	106	67	5	106	
Org	ENG	57	43	83	56	45	80	63	43	91	73	12	104	72	14	102	72	12	104	72	12	104	
	HIS	48	34	56	47	34	54	52	35	63	58	13	72	57	14	70	58	13	72	58	13	72	
Red	ENG	30	53	47	28	54	43	35	54	56	34	26	53	33	29	51	35	28	55	33	26	52	
	HIS	24	47	37	23	48	35	29	47	47	29	22	46	28	25	45	30	23	47	28	23	45	
	VIP	31	57	48	29	58	45	37	57	59	36	29	56	35	32	55	37	30	58	35	29	55	
Brn	ENG	29	21	35	28	21	34	31	24	38	33	11	41	32	13	40	33	12	41	33	11	41	
	HIS	25	17	27	25	17	26	28	19	30	30	6	35	30	7	34	30	7	35	30	6	34	

Table 4 (continued): CIE LAB Coordinates for Sign Colors

		M2h			M2u			M4h			M4u			F30			F35			F41			F65		
		L	A	B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	B	L	A	B
Whi	ENG	73	-2	5	73	-2	6	73	-2	5	73	-2	6	73	-2	5	73	-2	5	73	-2	5	73	-3	5
	HIS	64	-1	0	64	-1	0	64	-1	0	64	-1	0	64	-1	-1	64	-1	-1	64	-1	-1	64	-1	-1
	VIP	70	-2	-2	70	-1	-2	70	-2	-2	70	-1	-2	70	-2	-3	70	-2	-3	70	-2	-3	71	-1	-2
Blu	ENG	14	-2	-54	13	5	-54	15	0	-53	13	1	-55	10	2	-59	12	6	-59	13	11	-57	16	23	-53
	HIS	18	-8	-54	16	2	-56	18	-6	-52	16	-4	-56	15	-8	-59	16	-3	-58	17	1	-56	20	15	-51
	VIP	12	-5	-44	12	4	-47	13	-3	-43	12	-1	-46	11	-7	-50	12	-3	-47	13	2	-46	15	13	-42
Grn	ENG	25	-52	-9	24	-47	-6	26	-54	-7	24	-49	-8	23	-46	-8	24	-47	-6	25	-49	-3	28	-52	3
	HIS	26	-57	-7	25	-52	-4	27	-59	-5	25	-54	-6	25	-53	-3	27	-54	-1	28	-55	1	31	-57	7
	VIP	25	-54	-9	24	-49	-6	26	-56	-7	24	-51	-8	23	-48	-8	24	-49	-6	25	-51	-3	28	-54	4
Yel	ENG	70	13	99	71	7	102	69	13	98	71	10	101	71	9	99	70	9	99	70	8	99	67	5	98
	HIS	52	15	85	53	10	87	51	15	85	53	12	87	53	14	86	52	14	86	52	14	85	50	11	82
	VIP	61	18	98	62	13	100	61	18	97	62	15	99	62	18	97	61	18	98	60	18	97	58	15	94
Org	ENG	62	38	89	62	32	91	61	39	88	63	34	91	60	51	87	58	52	85	57	53	82	52	54	75
	HIS	51	29	59	51	24	58	50	30	58	51	26	60	52	37	60	51	37	59	50	38	58	46	37	53
Red	ENG	27	42	42	25	37	39	27	43	41	27	39	42	35	49	55	33	50	53	32	51	51	28	52	44
	HIS	23	37	34	21	33	31	22	39	33	23	34	34	29	43	45	27	44	44	26	46	42	23	47	36
	VIP	28	46	43	26	41	39	28	47	42	28	42	42	38	53	59	36	55	57	35	56	54	30	57	47
Brn	ENG	29	18	35	29	14	35	29	18	35	30	16	36	32	22	40	32	22	40	31	22	39	29	19	36
	HIS	26	14	29	27	12	29	26	15	28	27	13	30	27	17	30	26	17	29	26	17	28	24	16	25

Table 5 summarizes the data in Tables 3 and 4. All of the illuminants in Table 3 except Equal Energy were combined into a set called "Most". The average and standard deviation of the reflectance values for the "Most" set were calculated and reported in Table 5, along with the corresponding Uniformity Index (U.I. = 1 – StDev / Avg). Table 5 also shows the average and standard deviation values and averaged L*a*b* coordinates calculated separately for just the Metal Halide or High Pressure Sodium illuminants.

Table 5: Summary of Reflectance and LAB Coordinates for “Most” and HPS and MH Illuminants

		“Most” Reflectances			Averaged Reflectances					HPS			MH		
		Average	StDev	U.I.	HPS	StDev	MH	StDev	HPS/MH	L	A	B	L	A	B
White	ENG	45%	0.1%	1.00	45%	0.0%	45%	0.0%	1.0	73	-1	4	73	-2	6
	HIS	33%	0.2%	1.00	33%	0.0%	33%	0.0%	1.0	64	-1	-1	64	-1	0
	VIP	41%	0.3%	0.99	41%	0.1%	41%	0.0%	1.0	70	-1	-3	70	-2	-2
Blue	ENG	1.4%	0.6%	0.61	0.8%	0.1%	1.7%	0.2%	0.5	7	-3	-71	14	1	-54
	HIS	2.0%	0.9%	0.57	0.8%	0.1%	2.4%	0.2%	0.4	8	-8	-72	17	-4	-55
	VIP	1.2%	0.5%	0.59	0.5%	0.1%	1.5%	0.1%	0.4	5	-4	-56	12	-1	-45
Green	ENG	3.7%	1.5%	0.60	1.6%	0.0%	4.3%	0.3%	0.4	14	-26	-30	25	-51	-8
	HIS	4.1%	1.8%	0.57	1.6%	0.1%	4.7%	0.4%	0.3	13	-30	-30	26	-56	-6
	VIP	3.7%	1.5%	0.60	1.6%	0.0%	4.3%	0.4%	0.4	13	-28	-30	25	-53	-8
Yellow	ENG	42%	4.1%	0.90	48%	0.1%	41%	1.0%	1.2	75	3	105	70	11	100
	HIS	21%	2.5%	0.88	25%	0.2%	20%	0.5%	1.2	57	5	92	52	13	86
	VIP	31%	4.1%	0.87	37%	0.2%	30%	0.8%	1.2	67	5	105	62	16	99
Orange	ENG	32%	8.3%	0.74	44%	0.7%	30%	1.0%	1.5	72	13	104	62	36	90
	HIS	21%	3.7%	0.82	26%	0.4%	19%	0.5%	1.4	58	13	72	51	27	59
Red	ENG	6.7%	1.5%	0.78	7.8%	0.4%	4.9%	0.3%	1.6	34	27	53	27	40	41
	HIS	4.7%	1.0%	0.78	5.7%	0.3%	3.6%	0.2%	1.6	29	23	46	22	36	33
	VIP	7.5%	1.8%	0.76	8.8%	0.5%	5.3%	0.3%	1.7	36	30	56	28	44	42
Brown	ENG	6.6%	0.7%	0.89	7.5%	0.1%	6.0%	0.1%	1.2	33	12	41	29	17	35
	HIS	5.2%	0.7%	0.86	6.2%	0.1%	4.9%	0.1%	1.3	30	7	35	27	14	29

The results in Tables 3, 4 and 5 show a notable difference in the reflectance of the same colored sample under different illuminants. The white films are the most consistent of all the colors, with standard deviation at or near zero and U.I. at 1.0 for “Most” sources.

The blue films have a reflectance range from 0.5% (H10 and H25 with VIP series) to 3.5% (C_D with HIS series). Illuminant C_D has the highest reflectance of any source within each of the series of blue films while the HPS illuminants have the lowest reflectance values within the series. MH illuminants will produce between 1 to 6 times the brightness produced by HPS illuminants. However, even that increased brightness is near the value of 2% used for black, so the additional effectiveness of that brightness may be small. There is a clear trend that sources with high CCT values produce higher reflectances than sources with low CCT values.

Green films' reflectance values range from 1.5% (H10 and HIS series) to 6.5% (C_D and HIS series) meaning that an HIS series green sign will be 4 to 5 times as luminous under a D65 source as under an H10 source. Metal halide sources will produce around three times the brightness produced by HPS illuminants.

Yellow films' reflectance values vary the least of any colored (e.g. not white) surface, with a U.I. of 0.88 to 0.90. The most reflective film and source combination produces 48% reflectance (HPS and ENG series), and HPS sources produce the highest reflectances in all three series of films. The lowest reflectance values are 17% (C_D and HIS series) and 18% (EqE and F65 with HIS series) indicating that the brightness of yellow is lower under sources with high CCT values. Brightness of yellow under HPS or MH is roughly equal, with the HPS sources producing slightly higher reflectances.

For orange films the reflectances range from 44% (HPS and ENG series) to 16% (F65 and HIS series). Metal halide sources will produce around two-thirds the brightness produced by HPS illuminants.

Red films' reflectances vary from 8.5% (C_A and ENG series) to 3.3% (M2h and HIS series). The differences between HPS and MH are evident, with the reflectances under HPS about five-thirds of the reflectances under MH. A trend clearly appears, that sources with lower CCT values produce greater reflectance values for red than do sources with higher CCT values.

The reflectances for brown films range from 7.6% (H25 and ENG series) to 4.2% (F65 and HIS series) while the U.I. for the "Most" sources is higher than for any other color except yellow.

On first thought it would appear that the use of sources that produce a higher reflectance would be advantageous, but this is not necessarily the case because a higher luminance does not necessarily yield better visibility. Visibility is based on the ability to distinguish contrast or - more importantly for a foveal based task - color difference. The combination of colors in view is the key component in a foveal task’s visibility. Common sign color combinations are White and Red, Orange and Black, Yellow and Black and White and Green. The luminous contrast and delLAB values for these combinations of colors are shown in Tables 6-9.

Table 6: Luminous Contrast (C and C_{mod}) and delLAB (dLAB) Values for Sign Color Combination Red-White

	ENG Series			Red	Whi	HIS Series			Red	Whi	VIP Series			Red	Whi
Source	C	Cmod	dLAB	L*	L*	C	Cmod	dLAB	L*	L*	C	Cmod	dLAB	L*	L*
Equal Energy	0.86	0.76	82	30	73	0.87	0.77	74	24	64	0.84	0.72	87	31	70
CIE D65	0.88	0.78	82	28	73	0.89	0.80	74	23	64	0.86	0.75	87	29	71
CIE Illuminant A	0.81	0.68	85	35	73	0.82	0.70	77	29	64	0.77	0.62	92	37	70
HPS 100W	0.83	0.70	68	34	73	0.83	0.70	63	29	64	0.78	0.64	74	36	70
HPS 150W	0.83	0.72	69	33	73	0.83	0.72	64	28	64	0.79	0.66	75	35	70
HPS 250W	0.81	0.69	70	35	73	0.81	0.69	64	30	64	0.77	0.62	76	37	70
HPS 400W	0.83	0.71	68	33	73	0.83	0.71	63	28	64	0.79	0.66	74	35	70
MH 250W Horiz	0.89	0.80	74	27	73	0.89	0.80	65	23	64	0.87	0.76	78	28	70
MH 250W Univ	0.90	0.82	70	25	73	0.90	0.82	63	21	64	0.88	0.79	73	26	70
MH 400W Horiz	0.89	0.80	74	27	73	0.89	0.80	67	22	64	0.87	0.77	78	28	70
MH 400W Univ	0.89	0.80	71	27	73	0.89	0.80	64	23	64	0.87	0.76	74	28	70
Fluorescent 3000K	0.81	0.68	81	35	73	0.83	0.70	73	29	64	0.76	0.62	89	38	70
Fluorescent 3500K	0.83	0.71	81	33	73	0.84	0.72	74	27	64	0.78	0.64	89	36	70
Fluorescent 4100K	0.84	0.73	81	32	73	0.85	0.75	74	26	64	0.80	0.67	89	35	70
Fluorescent 6500K	0.88	0.78	81	28	73	0.89	0.80	73	23	64	0.85	0.74	86	30	71

Table 7: Luminous Contrast (C and C_{mod}) and delLAB (dLAB) Values for Sign Color Combination Orange-Black

	ENG Series			Org	Blk	HIS Series			Org	Blk
Source	C	Cmod	dLAB	L*	L*	C	Cmod	dLAB	L*	L*
Equal Energy	0.92	0.85	102	57	15	0.88	0.79	73	48	15
CIE D65	0.91	0.84	101	56	15	0.88	0.78	71	47	15
CIE Illuminant A	0.94	0.88	112	63	15	0.90	0.82	81	52	15
HPS 100W	0.95	0.91	120	73	15	0.92	0.86	85	58	15
HPS 150W	0.95	0.91	118	72	15	0.92	0.85	83	57	15
HPS 250W	0.95	0.91	119	72	15	0.92	0.86	85	58	15
HPS 400W	0.95	0.91	119	72	15	0.92	0.86	85	58	15
MH 250W Horiz	0.93	0.87	108	62	15	0.89	0.81	75	51	15
MH 250W Univ	0.93	0.88	107	62	15	0.90	0.81	72	51	15
MH 400W Horiz	0.93	0.87	107	61	15	0.89	0.80	74	50	15
MH 400W Univ	0.94	0.88	108	63	15	0.90	0.81	75	51	15
Fluorescent 3000K	0.93	0.87	110	60	15	0.90	0.82	80	52	15
Fluorescent 3500K	0.92	0.86	109	58	15	0.90	0.81	78	51	15
Fluorescent 4100K	0.92	0.85	106	57	15	0.89	0.80	78	50	15
Fluorescent 6500K	0.90	0.82	100	52	15	0.87	0.77	72	46	15

Table 8: Luminous Contrast (C and C_{mod}) and delLAB (dLAB) Values for Sign Color Combination Yellow-Black

	ENG Series			Yel	Blk	HIS Series			Yel	Blk	VIP Series			Yel	Blk
Source	C	Cmod	dLAB	L*	L*	C	Cmod	dLAB	L*	L*	C	Cmod	dLAB	L*	L*
Equal Energy	0.95	0.90	111	67	15	0.89	0.80	91	50	15	0.92	0.86	106	58	15
CIE D65	0.94	0.89	108	66	15	0.89	0.79	89	49	15	0.92	0.85	105	57	15
CIE Illuminant A	0.95	0.91	112	70	15	0.90	0.82	94	53	15	0.93	0.88	110	62	15
HPS 100W	0.96	0.92	121	75	15	0.92	0.85	101	57	15	0.95	0.90	117	67	15
HPS 150W	0.96	0.92	120	75	15	0.92	0.85	100	57	15	0.95	0.90	116	67	15
HPS 250W	0.96	0.92	121	75	15	0.92	0.85	101	57	15	0.95	0.90	118	67	15
HPS 400W	0.96	0.92	121	75	15	0.92	0.85	101	57	15	0.95	0.90	118	67	15
MH 250W Horiz	0.95	0.91	114	70	15	0.90	0.82	94	52	15	0.93	0.87	110	61	15
MH 250W Univ	0.95	0.91	117	71	15	0.90	0.82	95	53	15	0.93	0.88	111	62	15
MH 400W Horiz	0.95	0.90	113	69	15	0.90	0.82	94	51	15	0.93	0.87	109	61	15
MH 400W Univ	0.95	0.91	116	71	15	0.90	0.82	96	53	15	0.93	0.88	111	62	15
Fluorescent 3000K	0.95	0.91	114	71	15	0.91	0.83	95	53	15	0.93	0.88	109	62	15
Fluorescent 3500K	0.95	0.91	114	70	15	0.90	0.82	95	52	15	0.93	0.87	110	61	15
Fluorescent 4100K	0.95	0.91	114	70	15	0.90	0.82	94	52	15	0.93	0.87	108	60	15
Fluorescent 6500K	0.95	0.90	111	67	15	0.89	0.80	90	50	15	0.92	0.86	104	58	15

Table 9: Luminous Contrast (C and C_{mod}) and delLAB (dLAB) Values for Sign Color Combination Green-White

	ENG Series			Grn	Whi	HIS Series			Grn	Whi	VIP Series			Grn	Whi
Source	C	Cmod	dLAB	L*	L*	C	Cmod	dLAB	L*	L*	C	Cmod	dLAB	L*	L*
Equal Energy	0.88	0.78	72	28	73	0.81	0.68	71	30	64	0.87	0.76	72	28	70
CIE D65	0.87	0.77	71	29	73	0.80	0.67	69	31	64	0.86	0.75	72	29	71
CIE Illuminant A	0.91	0.83	74	24	73	0.86	0.75	71	26	64	0.90	0.81	73	24	70
HPS 100W	0.96	0.93	73	13	73	0.95	0.91	65	13	64	0.96	0.92	69	13	70
HPS 150W	0.96	0.93	72	14	73	0.95	0.90	65	14	64	0.96	0.92	68	14	70
HPS 250W	0.96	0.93	73	13	73	0.95	0.91	65	13	64	0.96	0.92	68	13	70
HPS 400W	0.96	0.93	73	14	73	0.95	0.91	65	13	64	0.96	0.92	69	13	70
MH 250W Horiz	0.90	0.82	71	25	73	0.85	0.74	68	26	64	0.89	0.80	69	25	70
MH 250W Univ	0.91	0.84	68	24	73	0.87	0.76	64	25	64	0.90	0.82	67	24	70
MH 400W Horiz	0.90	0.81	71	26	73	0.84	0.73	69	27	64	0.88	0.79	70	26	70
MH 400W Univ	0.91	0.84	69	24	73	0.87	0.76	66	25	64	0.90	0.82	68	24	70
Fluorescent 3000K	0.91	0.84	68	23	73	0.86	0.76	65	25	64	0.91	0.83	66	23	70
Fluorescent 3500K	0.91	0.83	67	24	73	0.85	0.74	65	27	64	0.90	0.81	66	24	70
Fluorescent 4100K	0.90	0.82	68	25	73	0.84	0.72	65	28	64	0.89	0.80	67	25	70
Fluorescent 6500K	0.88	0.78	67	28	73	0.80	0.67	65	31	64	0.87	0.76	69	28	71

Contrast values in Tables 6 through 9 include those for the Equal Energy source. The values for Equal Energy are the contrast values that would be assigned to that combination when reflectance is calculated using conventional lighting calculations that disregard the spectral characteristics of the films reflectances. The variance in the contrast values in Tables 6 through 9 for all the other sources is a clear indication that the spectrally significant effects in roadway signage should be considered.

For HPS source, the contrast values are consistent with a 0.04 maximum variation across the different wattages within the same series, and delLAB values are consistent with a variation of 2 units. Metal Halide sources' contrast values remain consistent with a variation of only 0.03 across the different wattages and color series combinations. The MH sources' delLAB values are also consistent with a maximum variation of 5 units within each series of color combinations across the different wattages/burning positions. Contrast and delLAB values for HPS are slightly lower than those of the MH illuminants for the red-white combination, and equal or higher for the others.

For the fluorescent sources, a clear trend is that as the color temperature increases the contrast increases. As the CCT increases the delLAB values remain constant or increase up to 4100K, and the delLAB values for the 6500K are either the same or lower. In general, the delLAB values for fluorescent sources are higher than those produced by the HPS of MH illuminants.

While there appears to be a strong corollary between luminous contrast and delLAB, that trend is not always followed. Most of the color combinations have the lowest luminous contrast values associated with the lowest delLAB values and the highest luminous contrast values associated with the highest delLAB values.

However, in a few of the combinations this trend is not followed – in the case of white and red, Illuminant A produces the lowest luminous contrast of any of the illuminants but produces the highest delLAB value. This can be explained by the L*a*b* calculation procedure in which the source is white balanced for the color space, which is how the human visual system responds to various light sources. Contrast calculations do not incorporate a white balance due to the fact that they are lumen based and hence contain no color information. In other words the white in any contrast calculation may not be exactly white but instead is tinted due to the spectral power distribution of the source.

Conclusions

For highly chromatic surfaces, a spectrally-informed methodology more accurately describes the surfaces' reflected radiation, producing a more realistic evaluation of the potential for visibility by reporting the entire color difference, and not just that part that is luminous difference. Since LAB shows that luminous difference is only part – and sometimes a small part - of total color difference, then limiting calculations to luminous metrics does not allow for appropriate modeling of foveal perception.

For foveal tasks, High Pressure Sodium illuminants provide equal or better luminous contrast for typical roadway lighting applications when compared with Metal Halide illuminants, with the exception of the red and white combination. The luminous contrast for this combination is reduced due to the higher reflectance of red under the HPS illuminant as shown in Table 2. Red under HPS is 1.6 to 1.7 times as reflective as red illuminated by Metal Halide. The increased luminance of red under HPS may compensate for the decrease in lettering luminous contrast within the sign by increasing the luminous contrast of the entire sign against its background. In addition, red and white signs are unlike other sign color combinations in that these signs are iconic in that their shape indicates their meaning – it is not necessary for most drivers to read these signs to understand their meaning. Therefore, it can be concluded that there is no great advantage or disadvantage of one source versus another for the illumination of roadway signage.

Also of note is the lack of correlation between the ‘Color Rendering Index’ of a source and its ability to produce high visibility for sign color combinations. Illuminant A and D65 both have a CRI of 100, but in certain color combinations produce the lowest contrast values and the lowest delLAB values. The Metal Halide sources have CRI values between 53 to 68 while the High Pressure Sodium sources’ CRI values are between 16 and 21, but the contrasts and delLAB values for many of the color combinations are much closer than would be expected given the discrepancies in their CRI values. There are color combinations in which the contrast and delLAB values for the High Pressure Sodium illuminants are higher than those same color combinations under the Metal Halide illuminants. CRI is not a valid metric for predicting visibility in roadway signage lighting applications.

Further work on this topic should include applying a model to evaluate the spectral effects of aging. Further work on this topic should also include an investigation into more surfaces and colors, the incorporation of the appropriate mesopic foveal spectral luminous efficiency function(s), and further investigation into appropriate color difference models such as CIE LAB with a particular interest in evaluating color differences.

Acknowledgements

This work was supported solely by Luminous Design, Inc. and Marshall Design, Inc. The authors appreciate the invaluable and generous assistance of Philips Lighting and 3M, while reserving all responsibility for this work to themselves.

References

1) Zelanski, P. and M.P. Fisher. 1999. *Color*, 3rd edition. Upper Saddle River, N.J.: Prentice Hall.

2) IESNA. 2000. *Lighting Handbook 9th Edition*. New York, NY: IESNA.

3) Wyszecki & Stiles. 1982. *Color Science*. New York, NY: J Wiley & Sons.

4) CIE, 1998. *CIE Photometric and Colorimetric Data,* CIE D-001-1988. Vienna, Austria: CIE.

5) Department of Transportation Federal Highway Administration (FHWA). *Manual on Uniform Traffic Control Devices*, (MUTCD) 23 CFR Part 655. FHWA.

6) CIE 1996. *Colorimetry 2nd Edition*, TR15.2 - 1986. Vienna, Austria: CIE.

7) CIE. 1995. *Method of Measuring and Specifying Colour Rendering Properties of Light Sources*, TR13.3. Vienna, Austria: CIE.