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COLORS OF RETROREFLECTIVE TRAFFIC SIGN MATERIALS WHEN ILLUMINATED BY HIGH-INTENSITY-DISCHARGE HEADLIGHTS

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16. Abstract

This analytical study evaluated the colorimetric properties of retroreflective traffic signs when illuminated by high-intensity-discharge (HID) headlamps. Two aspects were investigated: (1) colorimetric shifts of individual sign materials when illuminated by HID light sources as opposed to halogen, and (2) colorimetric separations of the red sign material from the yellow, orange, and brown sign materials when illuminated by HID light sources. Spectral reflectances of sign materials and spectral power distributions of HID (and halogen) light sources were used to derive the CIE tristimulus values for the sign materials. These values were then transformed into the CIELAB space—a perceptually uniform color space. The results of the analyses indicate that the magnitude of the colorimetric shift increased with increasing correlated color temperature of the light source. The resulting colorimetric separations of red from yellow, orange, and brown for the HID light sources also tended to increase with increasing correlated color temperature, with the highest-temperature HID light source tested yielding greater colorimetric separations than halogen.

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The development of high-intensity-discharge (HID) headlights has raised questions regarding the color rendition of objects they illuminate. The human visual system is able to maintain color constancy under a wide range of natural daylight and, to a lesser extent, halogen light. The spectral power distributions (SPDs) of discharge lights, however, differ a great deal from those of natural light or halogen. Unlike the continuous SPDs of daylight or halogen, the SPDs of HID lights are characterized by high concentrations of energy at certain wavelengths, adjacent to other wavelength intervals having little or no energy. In the extreme, such lights may confuse the perceptual system. For example, consider the case of low pressure sodium light. Since all the emitted light is at one wavelength (589 nm), all the light reflected to the eye from an illuminated object will necessarily be of this wavelength. Thus the appearance of colored surfaces under low pressure sodium is quite distorted (Jerome, 1977; Collins, 1988).

While the metal halide HID lamps which are being developed for use in headlights do not present such an extreme, they are characterized by a series of fairly discrete spikes. This discontinuity does not in itself pose a problem for color vision, so long as the SPD provides sufficient energy across the entire visible spectrum (Thornton, 1977). However, some of these HID sources are lacking in energy in certain ranges of the spectrum, notably at long wavelengths. This has led to concern about the rendering of red under such lights. Furthermore, given that we are concerned with color perception in the nighttime viewing situation, problems of color-rendition for headlamps might be compounded by the fact that color perception is poorer at lower levels of illumination.

What might be the practical consequences of headlights with poor color rendering abilities? In many cases, these may be purely aesthetic. However, there may also be safety-related consequences. One important use of color in the real-world driving situation is to aid in the identification of traffic signs. If, for example, drivers are slower to identify a stop sign because the color is not easily recognized as red, this would present a safety concern. Therefore, the present study evaluated the colors of traffic signs due to their importance to driving safety, with a special emphasis on red signs.

In addressing the issue of color rendition under HID headlamps, we chose to begin by doing an analytical study. There are several advantages to this approach. First, we can study the problem at the most general level, free of practical concerns about the particular optics which will be used. Second, once the computer programming is in place to do the necessary calculations, it is a simple matter to generate a new analysis for any additional combination of light and sign material, therefore easily extending the range of applicability of the results. This is of importance since there is no single HID light, but rather a wide range of these lights, each with its own spectral power distribution, and resulting correlated color temperature and chromaticity.

PREVIOUS RELATED STUDIES

Naming Errors

Several previous studies of the effect of discharge light sources on perceived color yield reason for concern. Jerome (1977) tested color naming of ANSI safety colors under six different types of light sources (fluorescent daylight, incandescent, metal halide, deluxe mercury, clear mercury, and high pressure sodium). Significant color confusions (misnaming errors) were found under all light sources other than fluorescent daylight. Of particular relevance to the present study, there were significant confusions under metal halide HID lighting between red and orange, green and blue, and gray and yellow.

More recent studies at the National Bureau of Standards (Collins, 1987; Collins, Kuo, Mayerson, Worthey, and Howett, 1986) tested the identifiability of a large number of safety colors (of ordinary, fluorescent, and retroreflective composition) viewed under diffuse illumination from a range of different sources (including tungsten and metal halide HID). Subjects were asked to name the colors, using a restricted set of color terms, as well as to indicate the lightness, and primary and secondary hues. The percentage of names which agreed with the nominal color of the sign material was surprisingly low in many conditions. For example, under metal halide HID illumination, three of the different nominally red samples were unambiguously labelled as red on only 40% of trials. (It is important to point out, however, that even under tungsten light, "correct" naming of colors was well below 100%.)

A related paper (Collins, 1988) was concerned specifically with the colors used for highway traffic signs. This study reanalyzed a subset of the earlier data (Collins, 1987). Based on visual inspection as well as colorimetric specifications, colors were selected from the data set which closely matched the centroid colors (red, yellow, orange, brown, green, blue, black and white) specified by FHWA standards. The color-naming data were used to determine, for each color, which sign material was most accurately identified under the range of lights used.

Hussain, Arens, and Parsonson (1989) included HID lamps among the nine light sources that were used to illuminate *non-retroreflective* highway sign materials. The overall correct color recognition ranged from 72% for fluorescent to 20% for low-pressure sodium, with tungsten and two metal halide HIDs yielding 69, 68, and 61%, respectively. For the red sign sample tested, the correct color recognitions ranged from 94% for tungsten to 0% for low-pressure sodium, with the two metal halide HIDs yielding 73 and 58%, respectively.

Discriminability vs. Colorimetric Shift

Jerome (1977) examined the relationship between correct naming and special color rendering indices for the ANSI safety colors. These indices are measures of the colorimetric shifts for a given color which result when the illuminant is changed from the light of interest to a reference light (daylight or tungsten) of the same correlated color temperature. The color rendering indices were not predictive of correct naming.

Since the CIE (x,y) chromaticity space is *not* uniform (MacAdam, 1981), Jerome (1977) translated the CIE (x,y) chromaticity coordinates of the colors under each illuminant into the (U^*,V^*) coordinates of the 1964 CIE Uniform Chromaticity Space. He made the reasonable assumption that each color would most likely be confused with that color which is most similar to it, and which therefore has the smallest difference from it as measured in (U^*,V^*) units. He then plotted the percent correct identification for each color as a function of the (U^*,V^*) distance from its closest neighbor, to see whether this distance measure would be predictive of naming accuracy. While there was considerable scatter, it was the case that large (U^*,V^*) distances were associated with high accuracy, providing support for this approach.

Jerome (1977) concluded that "apparently the answer is not how faithfully the colors are rendered, but how well the colors can be perceived as different from the other colors. That is, if the red can be identified as red and not some other color, even though it may differ greatly from its daylight appearance, it is performing its function as a safety color satisfactorily. The above observations suggest that the important attribute for this application is the difference of each chromaticity from that of the other colors" (p. 182).

A similar logic was used by Collins (1987). Collins used the color-naming data to select for each color a single sample which was most accurately identified under all the light sources tested. The gamut of these colors in a uniform chromaticity space (CIELAB) was then compared against the gamut for the set of ANSI safety color samples. In line with Jerome's (1977) findings, these "best" colors were found to be more widely distributed in this space than were the ANSI colors. In other words, greater separability was associated with better identifiability.

GENERAL APPROACH

The present analytical study was designed to derive chromaticity coordinates of traffic-sign materials when illuminated by halogen and HID light sources, using the CIELAB uniform color space. CIELAB (to be described in more detail later) transforms standard tristimulus values into three new parameters: L*, a*, and b*. Two of these new coordinates (a* and b*) were used to address the following two independent questions:

(1) **How large is the colorimetric *shift* for each sign material when illuminated by HID light sources as opposed to halogen (the current standard in headlighting)?** To answer this question, two-dimensional distances were computed for each sign material by using the a* and b* coordinates. The computed colorimetric-shift distance is an index of the perceived *change* in the color of a given sign material under two different light sources.

The relationship between the size of chromaticity differences of two light sources and the resultant chromaticity shifts of sign materials is predictable if the light sources are incandescent. In that case, resultant shifts will be monotonically related to differences of chromaticities (and hence correlated color temperature) of the light sources. This is the case because incandescent lights have highly similar, continuous SPDs. However, such a relationship may or may not hold for light sources with discontinuous SPDs; there is no simple way to characterize or quantify the qualitative aspects of an SPD which determines its similarity to any other SPD.

(2) **How large is the colorimetric *separation* of the red from the other sign materials when illuminated by HID light sources as opposed to halogen?** To answer this question, two-dimensional distances were computed between the red sign material and its nearest three neighbors (yellow, orange, and brown) for each light source by using the a* and b* coordinates. The computed colorimetric distance is an index of the perceived *difference* between two sign materials under a given light source.

The basic computational steps involved in the present approach are summarized in Table 1.

TABLE 1

Basic computational steps involved in the present approach.

Step	Computation	Result	Figure/Table
1	Sum over all wavelengths from 400 to 700 nm of the following products: spectral reflectance of sign material × spectral power distribution of light source × CIE color-matching functions	X, Y, Z (CIE tristimulus values, normalized so that Y = 20)	
2	$x = X/(X + Y + Z)$ $y = Y/(X + Y + Z)$	x, y (CIE chromaticity coordinates)	Figures 16–43
3	$L^* = 116\ (Y/Y_n)^{1/3} - 16$ $a^* = 500\ [(X/X_n)^{1/3} - (Y/Y_n)^{1/3}]$ $b^* = 200\ [(Y/Y_n)^{1/3} - (Z/Z_n)^{1/3}]$ where X_n, Y_n, and Z_n are the tristimulus values for a reference white, normalized so that $Y_n = 100$	L^*, a^*, b^* (coordinates in the CIELAB space)	Figures 44–59
4	$[(a^*_h - a^*_{HID})^2 + (b^*_h - b^*_{HID})^2]^{1/2}$ where h = halogen (performed for each sign material and each HID light source)	Distance under halogen and HID light sources for each sign material	Tables 3–5
5	$[(a^*_{red} - a^*_i)^2 + (b^*_{red} - b^*_i)^2]^{1/2}$ where i = yellow, orange, or brown	Distances between red and yellow, orange, or brown for each light source	Tables 6–8

METHOD

Data on Traffic Sign Materials and Light Sources

The present analyses used relative spectral retroreflectance data for seven colors (white, red, yellow, orange, brown, green, and blue) in each of two grades of traffic sign materials (enclosed and encapsulated lens). The data were obtained under a 0.33° observation angle and a 5° entrance angle, at 10 nm intervals; linear interpolation was used to yield 1 nm interval data. The normalized spectral retroreflectance curves (400–700 nm) for the 14 sign materials are shown in Figures 1 through 7 (pages 19 through 25). (Because of the large number of figures, they are all included at the end of the report, starting on page 19.)

Spectral power distributions (in microwatts/nm) for seven metal halide HID light sources as well as for a halogen headlamp were used. Data for five of these sources were provided in 1-nm intervals; data for the other three were interpolated from 2-nm interval data. Correlated color temperatures and chromaticity coordinates of the light sources are given in Table 2. Normalized spectral power distributions for the light sources (400–700 nm) are shown in Figures 8 through 15 (pages 26 through 33).

TABLE 2
Correlated color temperatures and chromaticity coordinates of the light sources.

Light Source	Correlated Color Temperature (°K)	Chromaticity Coordinates	
		x	y
Halogen	3,018	.4366	.4056
HID-1	3,362	.4108	.3885
HID-2	3,564	.4001	.3845
HID-3	8,777	.2835	.3100
HID-4	3,564	.4126	.4185
HID-5	3,636	.4040	.4034
HID-6	4,328	.3782	.4208
HID-7	3,402	.4167	.4079

CIE (x,y) Chromaticity Coordinates

Standard colorimetric methods (Wyszecki & Stiles, 1982) were used to derive CIE (x,y) chromaticity coordinates for each combination of light source and sign material, thus yielding a total of 112 (8 x 14) data points. These data points were then plotted in two ways. The first set of graphs was designed to allow comparisons of chromaticities under each of the seven HID lights vs. halogen. (The comparison with halogen is of interest not because halogen illumination is necessarily superior, but rather because of its role as the standard in current headlighting practice.) These chromaticities are plotted separately for the two grades of sign materials (enclosed lens and encapsulated lens). The second set of graphs presents the same data, but here the focus is on the range of chromaticities for a single color under all eight light sources.

An obvious next step would have been to compare the resulting chromaticity locations with existing standards. However, there are no federal nighttime chromaticity standards for sign materials, except that the signs "shall be reflectorized or illuminated to show the same shape and colors both by day and night" (MUTCD, 1986, p. 2A-7). And, as Collins (1988) has pointed out, "no guidance is given for determining that the color is the same both by day and night" (p. 2). Because CIE chromaticity coordinates do not reflect the possible influence of such factors as chromatic adaptation, color contrast, or color constancy effects, it is not possible to predict directly color appearance from them. Whether the chromaticity of a sign illuminated by headlights at night falls within the CIE boundaries for a certain *daytime* color standard does not determine whether it "shows the same color."

CIELAB Data

Although using CIE chromaticity coordinates is the standard way to specify colors, they have the disadvantage of forming a non-uniform color space. This means that the distance between two points is not a measure of the perceived difference between the two colors those points represent. As pointed out by Jerome (1977), the discriminability of colors has a major effect on their identifiability. Therefore it would be very desirable to have a uniform representation of the present data which would provide information about the likely perceived differences of the colors when illuminated by the various light sources.

Mathematical transformations of the CIE color space have been developed which create new color spaces in which the property of uniformity is approximated. One such nonlinear transformation is the CIELAB space (CIE, 1978) which was used, for example, by Collins (1987). In this space, L^* represents lightness, the a^* axis represents a red(+)/

green(−) dimension, and the b* axis represents a yellow(+)/blue(−) dimension. A perfect white diffuser is assigned the coordinates L* = 100, a* = 0, b* = 0, and all other colors are evaluated in relationship to this white.

There are several ways one could use the CIELAB system to derive predictions about the discriminability of sign colors that would be expected under real-world conditions. For the daytime viewing situation, discriminability is most likely a function of the total color difference based on the L*, a*, and b* values for the two colors in question. However, the present study is concerned with nighttime viewing conditions. The method that we used was to set all L* values to a fixed, arbitrary constant, and to base distance calculations on the resulting values of a* and b*. The rationale for fixing the value of L* was that the perceived lightness of a retroreflective traffic sign illuminated by headlights is probably not a reliable cue to its identity, because of the large changes in sign luminance that occur as the intensity of incident light varies with the angular position and the distance of a sign relative to the headlights. Under some conditions an observer might be expected to compensate for these changes in incident light, thus achieving lightness constancy. However, at night retroreflective traffic signs are frequently seen as self-luminous objects against a dark background. Under such conditions an observer has no reliable basis on which to estimate the incident light, conditions under which lightness constancy has been shown to fail (Cornsweet, 1970; Wallach, 1948). Although an observer may not be able to estimate the intensity of light incident on an isolated sign, the spectral distribution of that light should be estimable because the distribution is the same throughout the visual field. Therefore, even if lightness constancy does not hold, an observer should show normal constancy for the chromatic aspects of color. Because these aspects are primarily reflected in a* and b*, distance based on those two parameters should give the best prediction of color discriminability. (The selected value of L* affects the absolute levels of a* and b*, but [in relation to other possible fixed values of L*] has no influence on any of the comparisons between the performances of the light sources.)

The CIELAB chromaticity data for all seven sign materials were plotted separately for each of the eight light sources and each grade of sign materials. In addition to this graphical representation, we also calculated (1) the *colorimetric shift* for each sign material when illuminated by HID light sources in comparison to halogen, and (2) the *colorimetric separation* of red from its three nearest neighbors (yellow, orange, and brown).

RESULTS

CIE (x,y) chromaticity plots for each of the seven HID sources (alongside halogen), and for each of the two grades of sign materials, are presented in Figures 16 through 29 (pages 34 through 47). (These figures also indicate the chromaticities of the light sources.) Chromaticity plots for single colors under the set of eight light sources are presented in Figures 30 through 43 (pages 48 through 54), separately for the two grades of sign materials.

Figures 44 through 59 (pages 55 through 62) plot the color gamuts in CIELAB (a^*b^*) chromaticity coordinates for each of the seven HID light sources (and halogen) and for the two grades of sign materials, with L^* set to an arbitrary constant (51.84). (This particular value of L^* followed from setting $Y = 20$.)

The information in Figures 44 through 59 was used to derive the colorimetric distances in Tables 3 through 8. Tables 3 through 5 present colorimetric shift-distances in CIELAB (a^*b^*) space for each sign material when illuminated by HID lamps as opposed to halogen. These distances were normalized in such a way that the smallest distance between two materials under halogen (orange and brown for enclosed lens) is equal to 100.

Data on colorimetric separations are presented in Tables 6 through 8, which present the colorimetric distances of red from its three nearest neighbors (i.e., yellow, orange, and brown). These distances were normalized to equal 100 for halogen.

Table 9 lists the HID light sources in the order of increasing correlated color temperature, and compares the light sources in terms of the average colorimetric shift and average colorimetric separation of red from yellow, orange, and brown.

TABLE 3

Colorimetric-shift distances of encapsulated-lens materials under halogen and HID lamps. (Normalized so that the smallest distance between two materials under halogen [orange and brown for enclosed lens] is equal to 100.)

Halogen vs.	Sign Material							Mean
	White	Red	Yellow	Orange	Brown	Green	Blue	
HID-1	36.6	177.3	72.1	108.9	110.9	97.9	222.1	118.0
HID-2	62.0	188.1	126.3	127.8	117.7	301.1	453.6	196.7
HID-3	79.0	198.9	278.8	190.6	268.7	453.8	884.5	336.3
HID-4	52.6	161.5	98.4	102.2	93.2	292.7	361.6	166.0
HID-5	57.6	154.6	115.6	99.0	93.8	326.1	425.0	181.7
HID-6	72.4	207.7	142.7	91.6	156.7	524.8	571.1	252.4
HID-7	50.1	138.4	100.4	100.6	69.0	263.5	354.5	153.8
Mean	58.6	175.2	133.5	117.2	130.0	322.8	467.5	200.7

TABLE 4

Colorimetric-shift distances of enclosed-lens materials under halogen and HID lamps. (Normalized so that the smallest distance between two materials under halogen [orange and brown for enclosed lens] is equal to 100.)

Halogen vs.	Sign Material							Mean
	White	Red	Yellow	Orange	Brown	Green	Blue	
HID-1	40.4	151.0	64.1	122.8	125.9	102.2	250.5	122.4
HID-2	65.3	163.2	123.9	135.4	178.5	277.6	772.6	245.2
HID-3	66.2	188.7	247.2	195.0	346.9	437.0	1330.6	401.7
HID-4	57.4	135.8	99.5	112.6	161.8	277.9	653.2	214.0
HID-5	60.9	131.9	116.7	111.4	167.8	302.8	785.4	239.6
HID-6	76.8	154.9	151.0	102.4	240.5	471.7	1274.4	353.1
HID-7	53.5	120.6	98.8	109.2	143.3	250.6	628.8	200.7
Mean	60.1	149.5	128.7	127.0	195.0	302.8	813.7	253.8

TABLE 5

Mean colorimetric-shift distances of both grades of sign material under halogen and HID lamps. (Normalized so that the smallest distance between two materials under halogen [orange and brown for enclosed lens] is equal to 100.)

Halogen vs.	Sign Material							Mean
	White	Red	Yellow	Orange	Brown	Green	Blue	
HID-1	38.5	164.2	68.1	115.8	118.4	100.0	236.3	120.2
HID-2	63.6	175.6	125.1	131.6	148.1	289.4	613.1	221.0
HID-3	72.6	193.8	263.0	192.8	307.8	445.4	1107.6	369.0
HID-4	55.0	148.6	99.0	107.4	127.5	285.3	507.4	190.0
HID-5	59.2	143.2	116.2	105.2	130.8	314.4	605.2	210.6
HID-6	74.6	181.3	146.8	97.0	198.6	498.2	922.8	302.8
HID-7	51.8	129.5	99.6	104.9	106.2	257.0	491.6	177.2
Mean	59.4	162.4	131.1	122.1	162.5	312.8	640.6	227.3

TABLE 6
Colorimetric separations of red from its three nearest neighbors (encapsulated lens).
(Normalized so that the corresponding separation under halogen is equal to 100.)

Light Source	Comparison Pair			Mean
	Red vs. Yellow	Red vs. Orange	Red vs. Brown	
HID-1	85.3	76.0	88.0	83.1
HID-2	97.1	78.6	101.6	92.4
HID-3	149.3	122.4	239.6	170.4
HID-4	98.5	81.5	101.0	93.7
HID-5	102.2	82.3	105.2	96.6
HID-6	103.6	72.0	131.8	103.6
HID-7	100.5	86.3	97.4	94.7
Mean	105.7	85.6	123.5	104.9

TABLE 7
Colorimetric separations of red from its three nearest neighbors (enclosed lens).
(Normalized so that the corresponding separation under halogen is equal to 100.)

Light Source	Comparison Pair			Mean
	Red vs. Yellow	Red vs. Orange	Red vs. Brown	
HID-1	78.3	83.1	87.7	83.0
HID-2	79.8	77.2	92.1	83.0
HID-3	99.3	98.5	128.8	108.9
HID-4	83.2	80.2	97.9	87.1
HID-5	85.3	80.5	99.0	88.3
HID-6	85.2	74.3	110.2	89.9
HID-7	85.6	83.4	96.9	88.6
Mean	85.2	82.5	101.8	89.8

TABLE 8

Colorimetric separations of red from its three nearest neighbors (means of both grades of sign material). (Normalized so that the corresponding separation under halogen is equal to 100.)

Light Source	Comparison Pair			Mean
	Red vs. Yellow	Red vs. Orange	Red vs. Brown	
HID-1	81.8	79.6	87.8	83.0
HID-2	88.4	77.9	96.8	87.7
HID-3	124.3	110.4	184.2	139.6
HID-4	90.8	80.8	99.4	90.4
HID-5	93.8	81.4	102.1	92.4
HID-6	96.0	73.2	121.0	96.8
HID-7	93.0	84.8	97.2	91.6
Mean	95.4	84.0	112.6	97.4

TABLE 9
Relation of light-source correlated color temperature, colorimetric shift, and colorimetric separation.

Light Source	Correlated Color Temperature (°K)	Colorimetric Shift (1 = smallest)	Colorimetric Separation (1 = greatest)
HID-1	3342	1	7
HID-7	3402	2	4
HID-4	3564	3	5
HID-2	3564	5	6
HID-5	3636	4	3
HID-6	4328	6	2
HID-3	8777	7	1

DISCUSSION

Colorimetric Shift for Sign Materials When Illuminated by HID Light Sources as Opposed to Halogen

The qualitative information in Figures 44 through 59, and the quantitative information in Tables 3 through 5 indicate that the largest colorimetric shift was for HID-3, followed by HID-6. For HID-3 the colorimetric shift averaged (for both grades of sign material) about 3.7 times the colorimetric separation of the nearest two sign materials under halogen (orange and brown for enclosed lens). The corresponding factor for the average colorimetric shift for HID-6 was 3.0. In comparison, the HID light source with the smallest average shift was HID-1 (1.2).

The encapsulated-lens sign materials yielded smaller colorimetric shifts than did the enclosed-lens materials (colorimetric-shift factors of 2.0 and 2.5, respectively). The blue materials were affected the most (average colorimetric-shift [for both grades of material] of 6.4), followed by green (3.1), brown (1.6), red (1.6), yellow (1.3), orange (1.2), and white (0.6).

Colorimetric Separation of Red from Other Sign Materials under HID Light Sources

The qualitative information in Figures 44 and 59, and the quantitative information in Tables 6 through 8 indicate that colorimetric separation of red from its nearest three neighbors (yellow, orange, and brown) was best under HID-3, followed by HID-6. For HID-3 the colorimetric separation averaged (for both grades of sign material) 1.4 times the corresponding colorimetric separation under halogen. The average colorimetric-separation factor for HID-6 was .97 (about the same as for halogen). In comparison, the HID light source with the smallest (worst) average colorimetric-separation factor was HID-1 (0.83).

Colorimetric Shift vs. Colorimetric Separation

The present data (Table 9) indicate that HID light sources that produced the largest colorimetric shift (HID-3 and HID-6), nevertheless yielded the best colorimetric separation of red from its nearest neighbors (yellow, orange, and brown). Conversely, the HID light source that produced the smallest colorimetric shift (HID-1), yielded the worst colorimetric separation of red from its nearest neighbors.

Correlated Color Temperature and Light Source Color Performance

In general, the higher the correlated color temperature of the HID light source, the larger was the resulting colorimetric shift (Table 9). On the other hand, the higher the correlated color temperature, the greater was the colorimetric separation of red from its three nearest neighbors (Table 9). In other words, while a light source having a high color temperature tends to lead to a large colorimetric shift, the resulting locations (at least for red and its neighbors) tend to be further apart than for a light source having a lower correlated color temperature. These findings suggest that, for the studied HID lamps, the correlated color temperature is a reasonable predictor of both colorimetric shift and colorimetric separation, despite the discontinuous nature of the SPDs.

Concluding Comments

How should we weigh colorimetric shift and colorimetric separation? Our view is that colorimetric separation should be of primary concern, *provided* that the corresponding colorimetric shift is not too large. The criteria for acceptable colorimetric shifts (e.g., shifts not crossing color-naming boundaries) need to be established empirically. From this perspective, our findings indicate that from among the studied HID headlamps, the one with the highest correlated color temperature (HID-3 [8,777°K] would likely yield better color rendition of traffic signs than halogen, provided that the obtained color shifts are found to be acceptable. The other six HID lamps studied would likely yield color rendition comparable to or somewhat poorer than halogen.

The current analytic study is not the final answer to the problem of color rendition of signs under HID lights. It may be desirable in the future to use the present results to predict actual human performance. For example, an experimental study might measure reaction times for the identification of red vs. non-red targets as a function of the type of the light source. Results of the current analytical study could be used to select and predict those combinations of lights and sign materials yielding colors which are easiest or most difficult to identify. If such results follow the colorimetric predictions closely, we may then be justified in using the analytical approach on its own.

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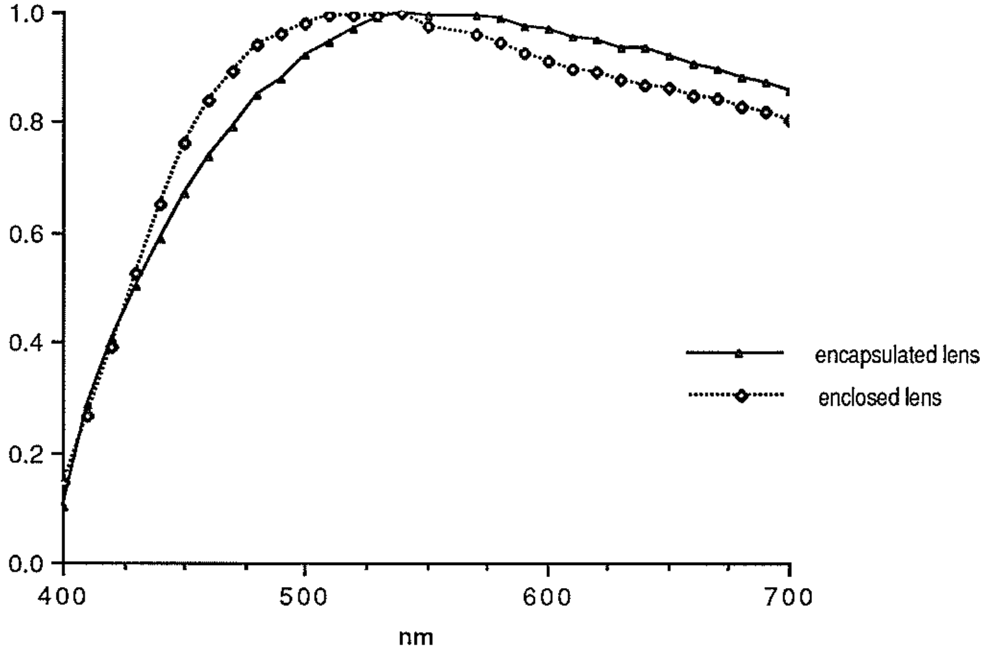


Figure 1. Relative spectral retroreflectance for white sign materials.

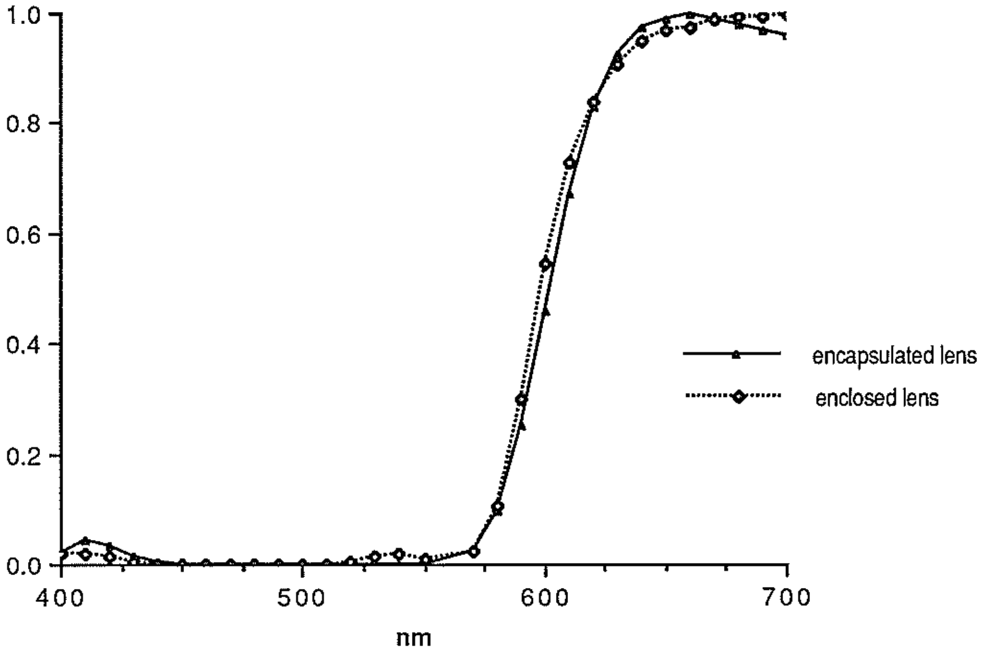


Figure 2. Relative spectral retroreflectance for red sign materials.

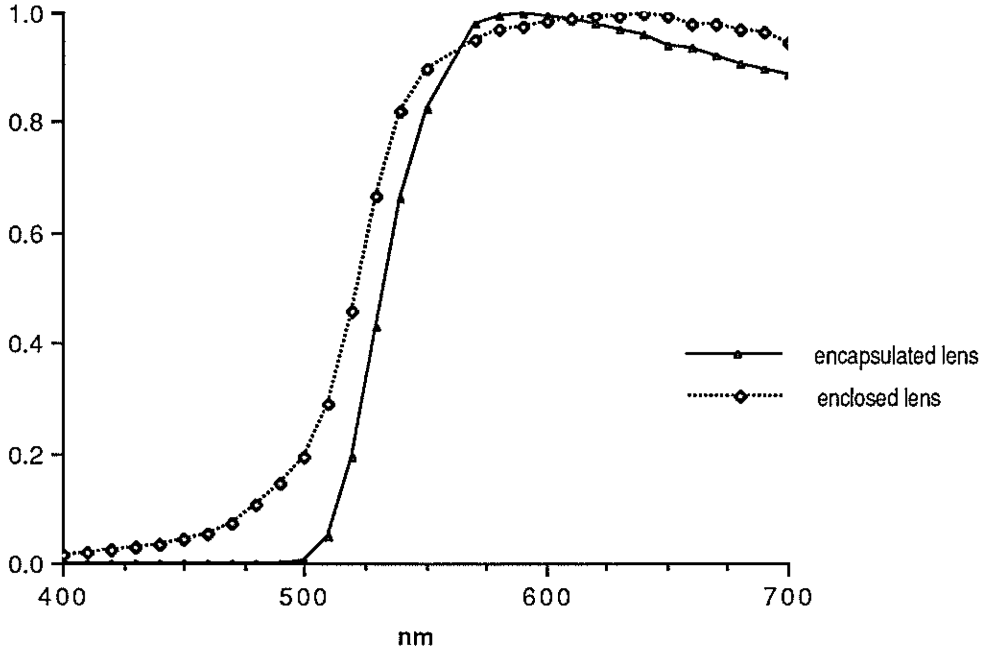


Figure 3. Relative spectral retroreflectance for yellow sign materials.

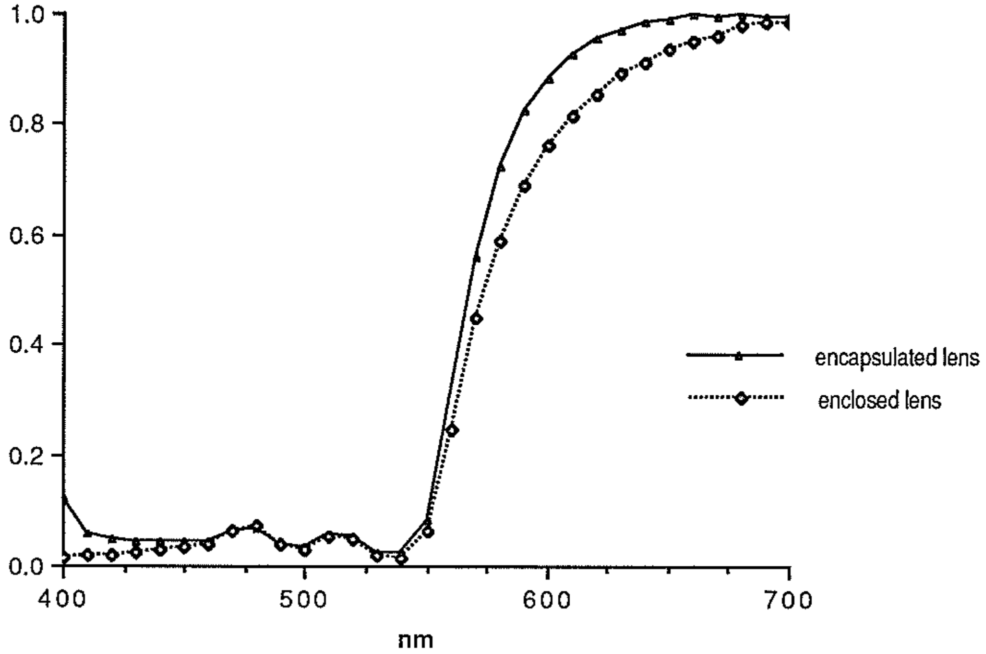


Figure 4. Relative spectral retroreflectance for orange sign materials.

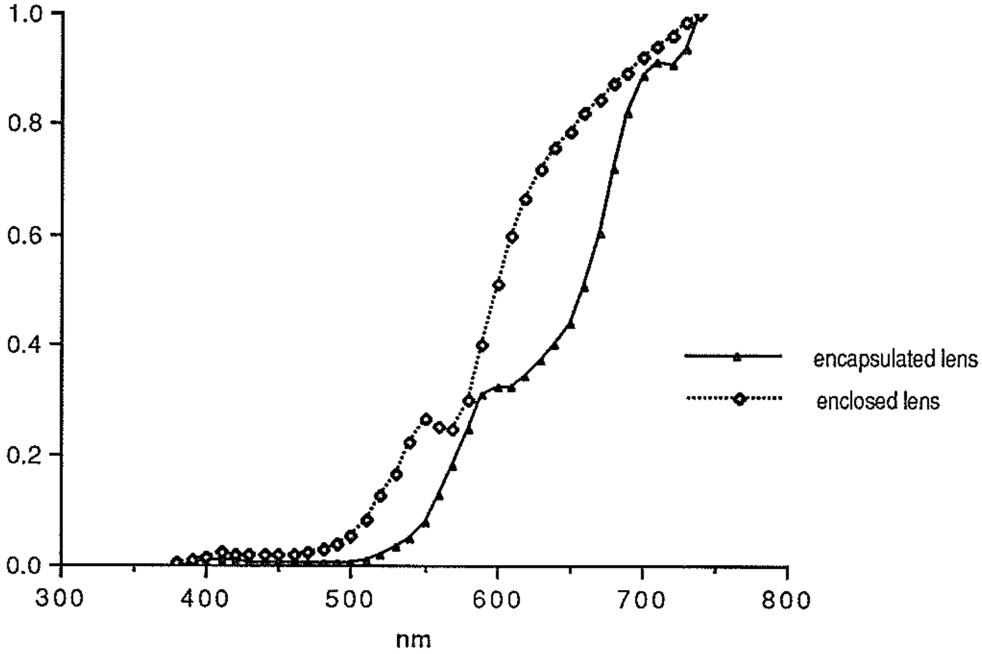


Figure 5. Relative spectral retroreflectance for brown sign materials.

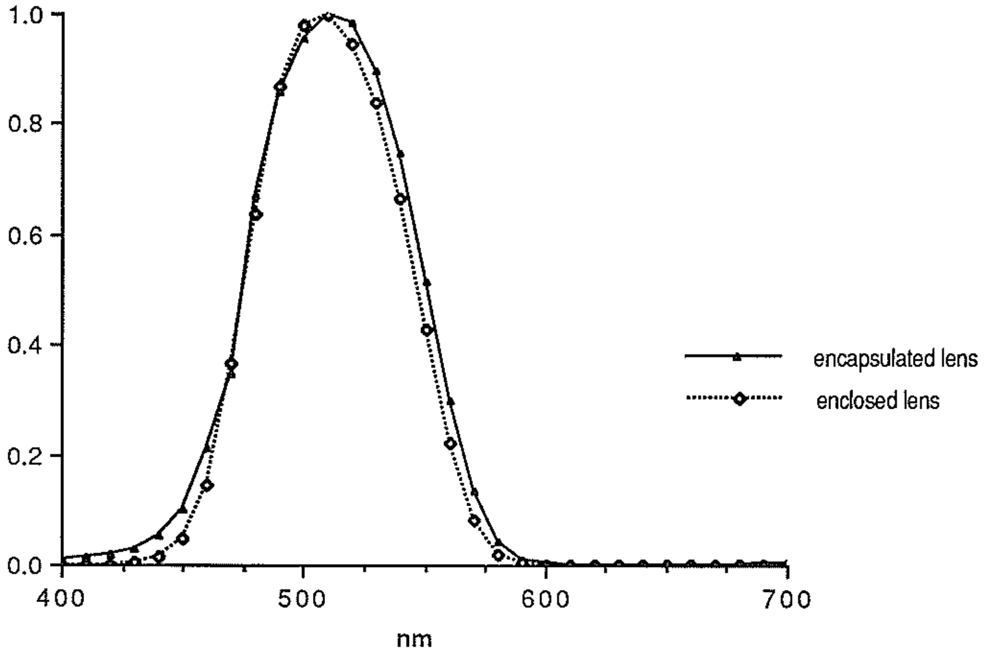


Figure 6. Relative spectral retroreflectance for green sign materials.

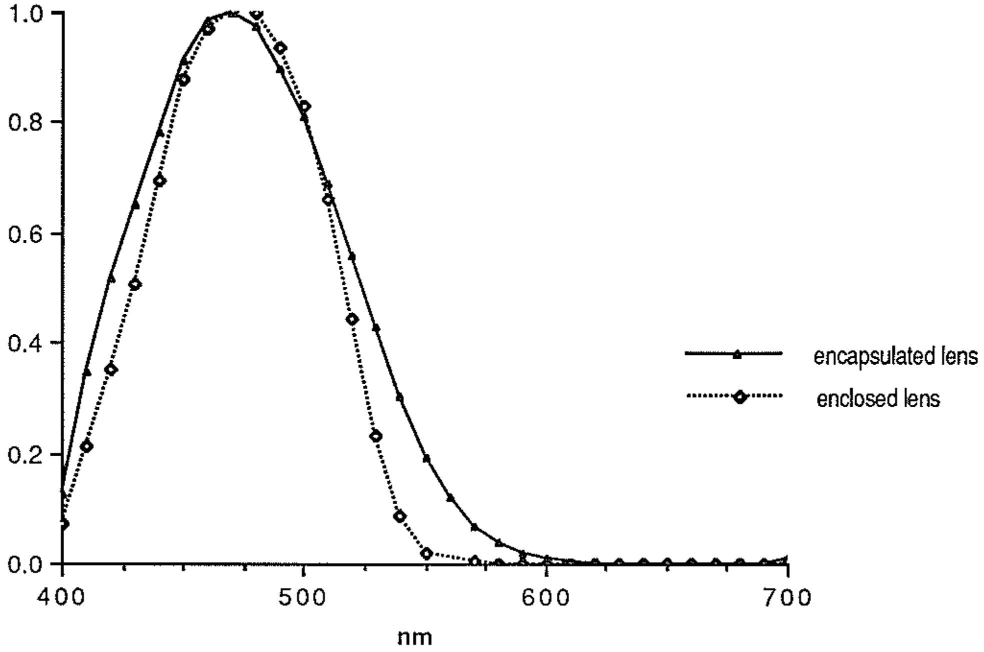


Figure 7. Relative spectral retroreflectance of blue sign materials.

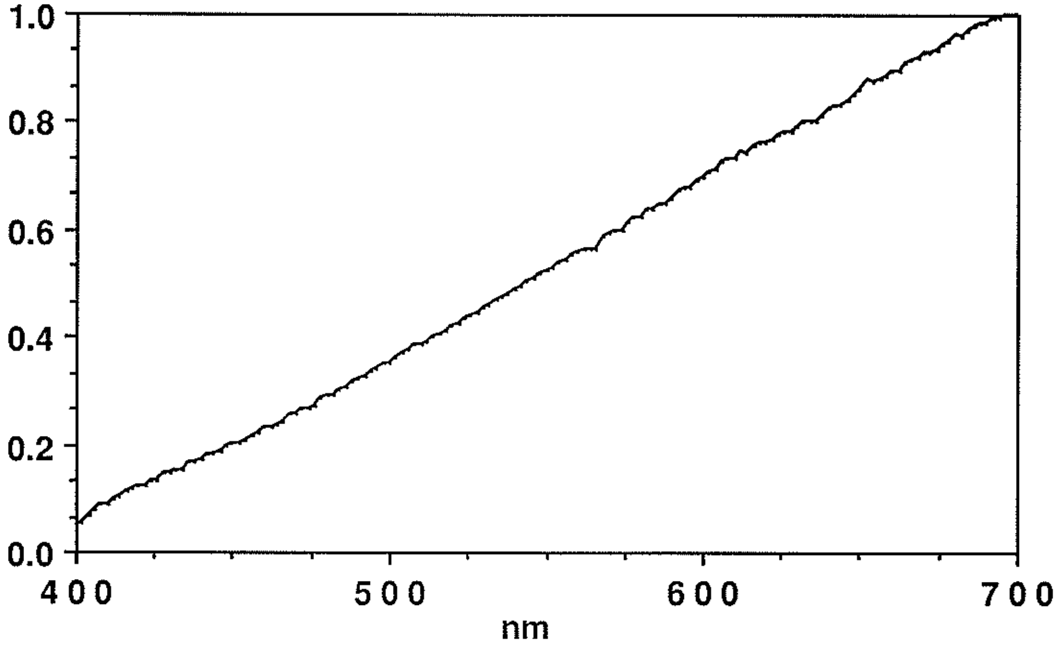


Figure 8. Relative spectral power distribution for halogen.

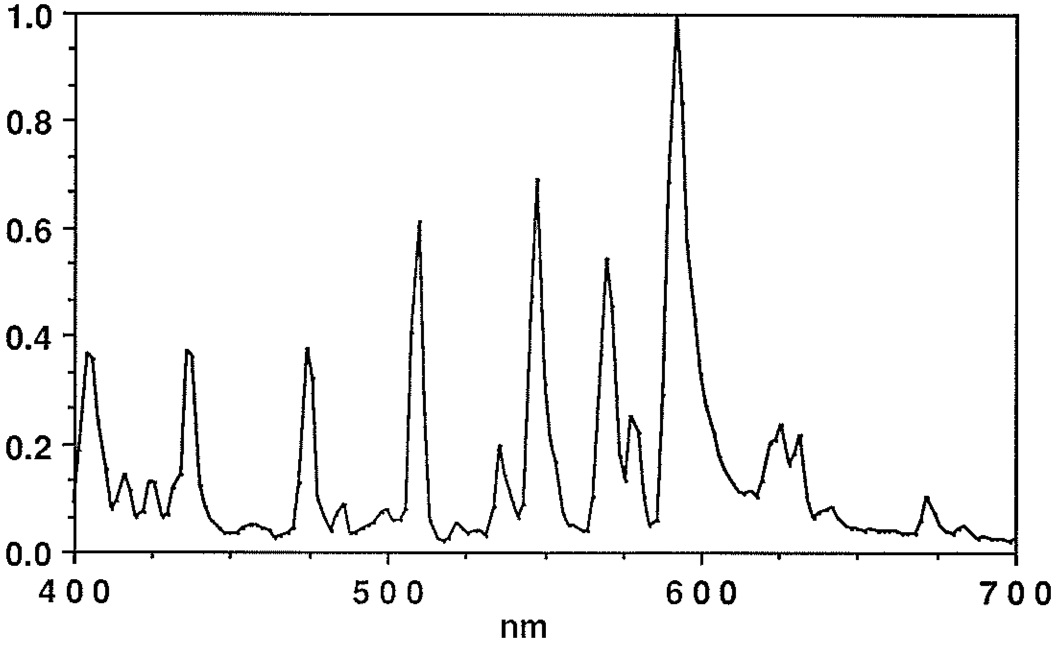


Figure 9. Relative spectral power distribution for HID-1.

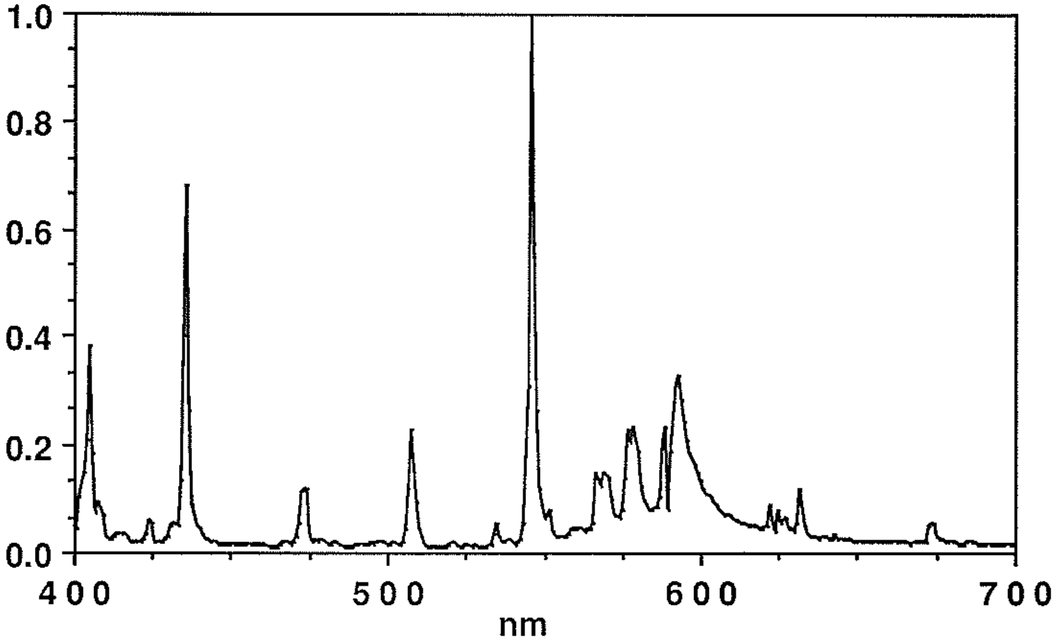


Figure 10. Relative spectral power distribution for HID-2.

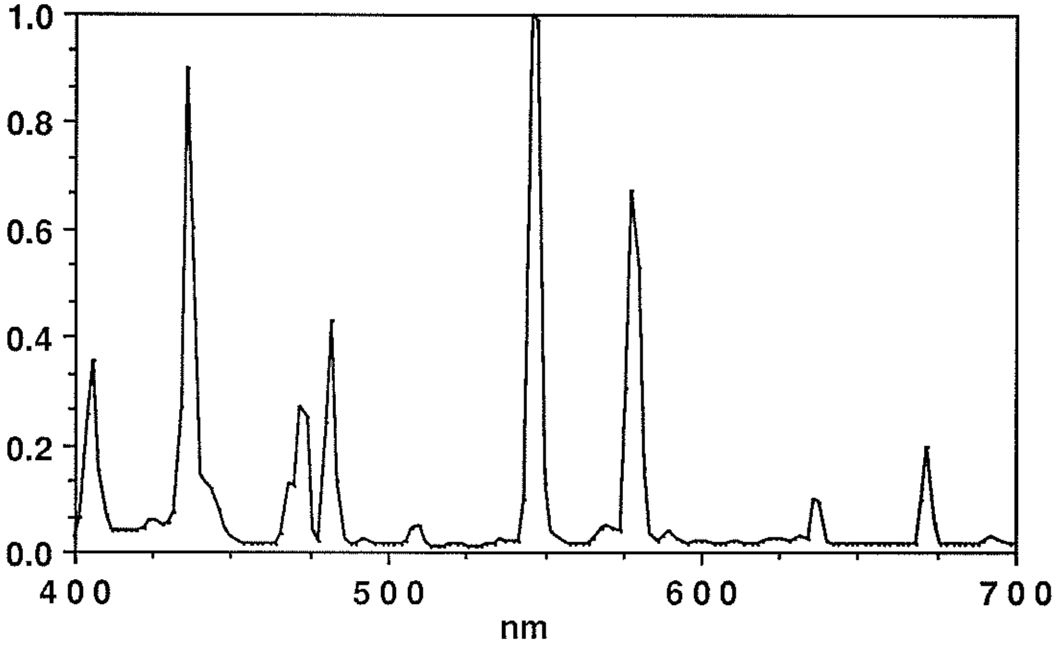


Figure 11. Relative spectral power distribution for HID-3.

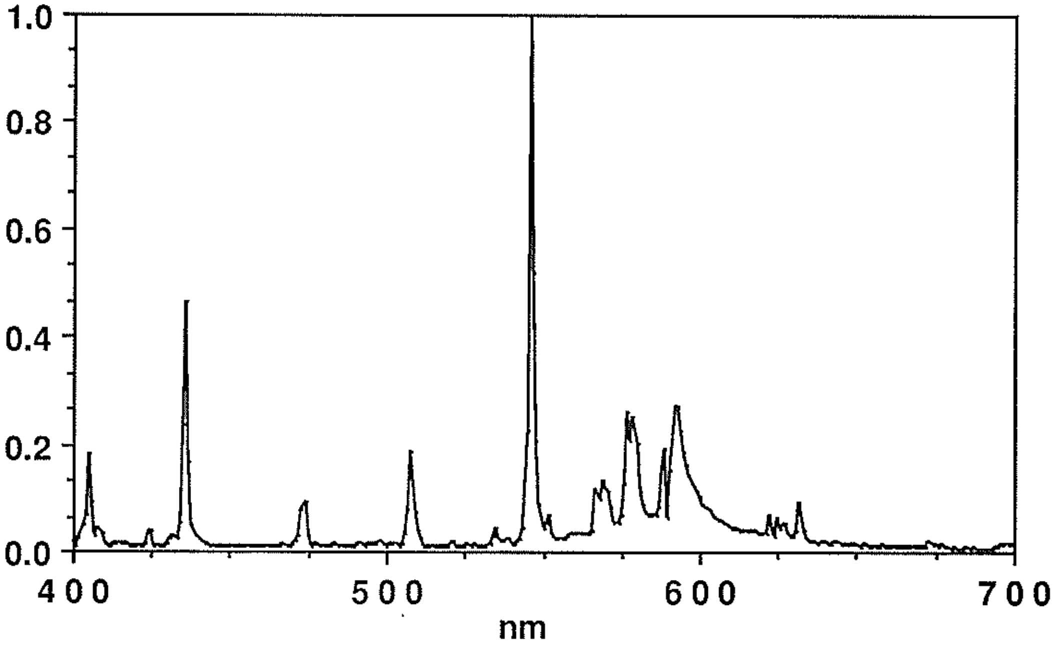


Figure 12. Relative spectral power distribution of HID-4.

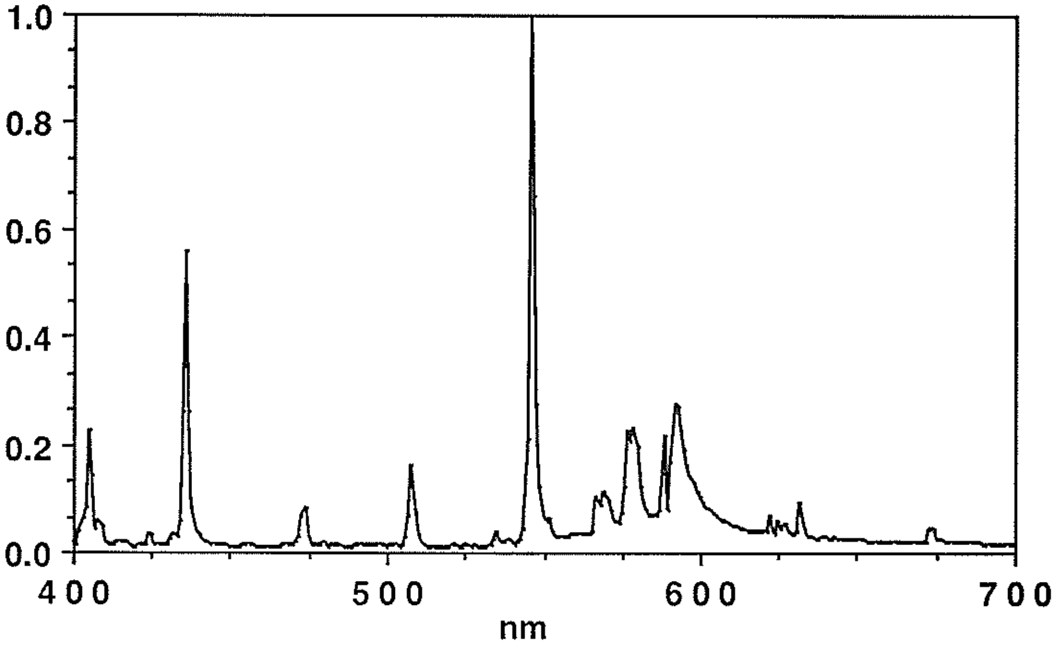


Figure 13. Relative spectral power distribution for HID-5.

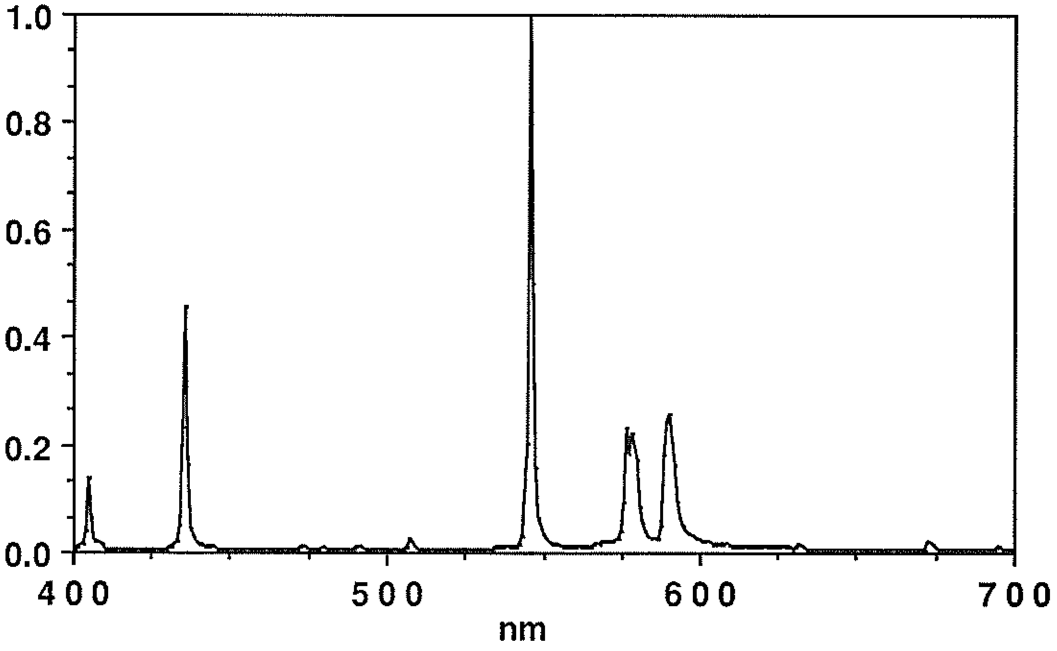


Figure 14. Relative spectral power distribution for HID-6.

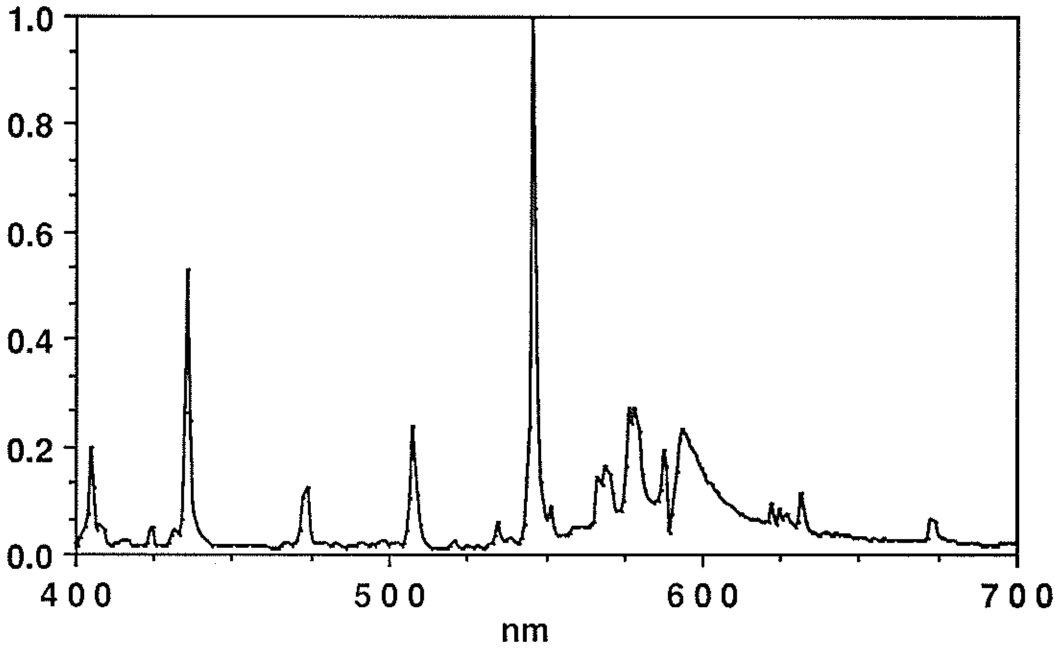


Figure 15. Relative spectral power distribution for HID-7.

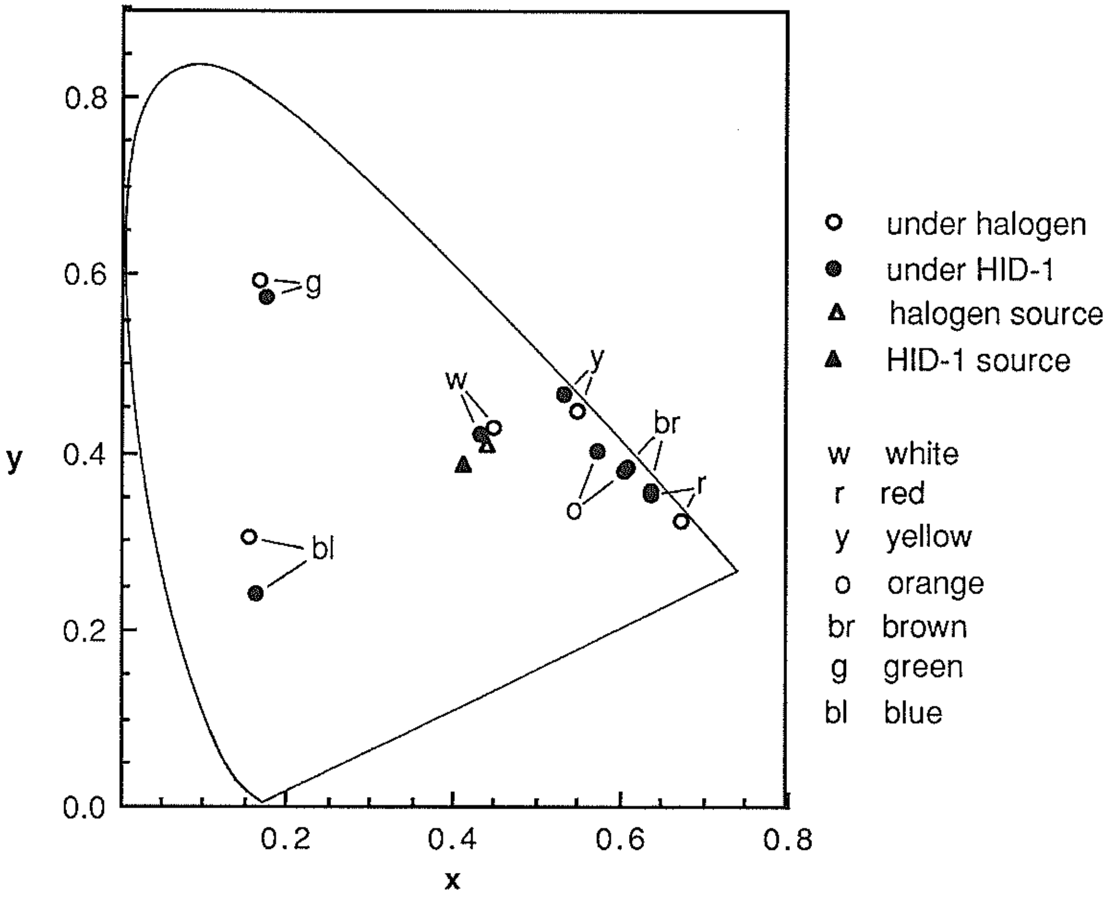


Figure 16. Chromaticities of the encapsulated-lens sign materials under HID-1.

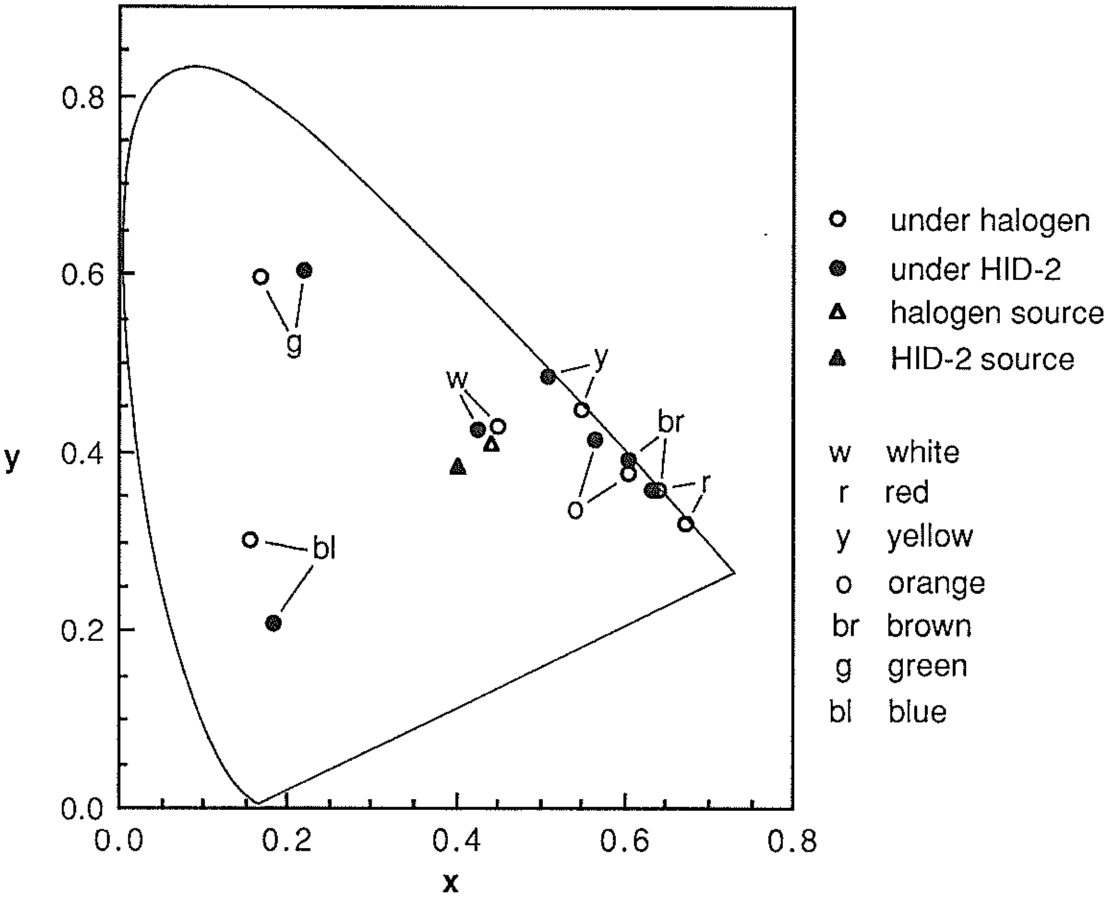


Figure 17. Chromaticities of the encapsulated-lens sign materials under HID-2.

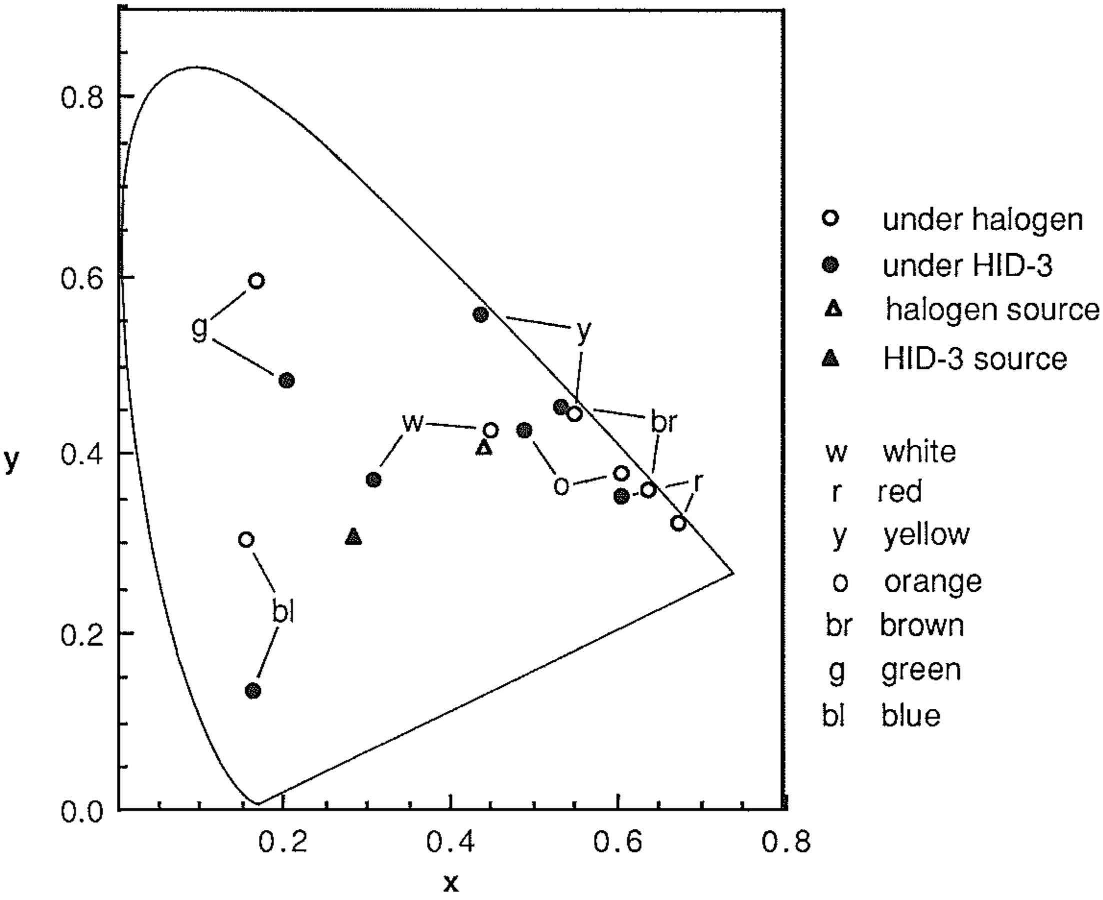


Figure 18. Chromaticities of the encapsulated-lens sign materials under HID-3.

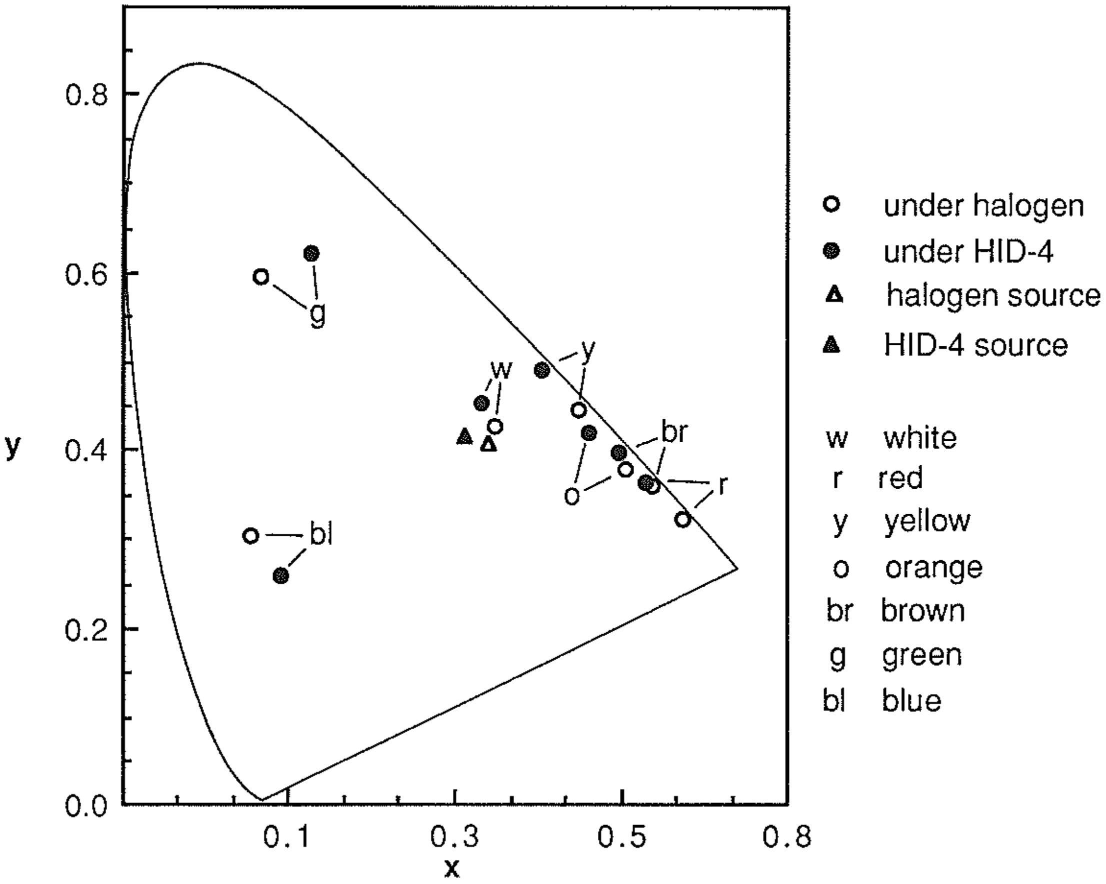


Figure 19. Chromaticities of the encapsulated-lens sign materials under HID-4.

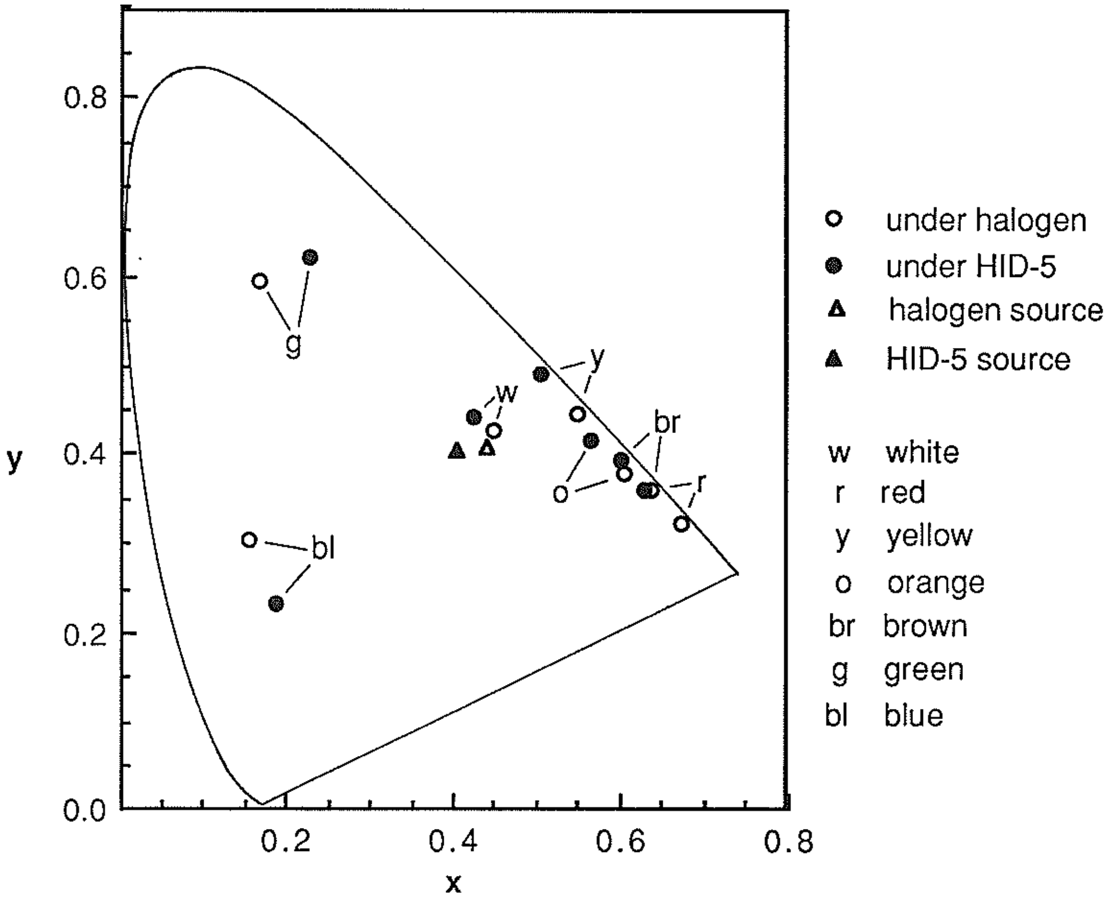


Figure 20. Chromaticities of the encapsulated-lens sign materials under HID-5.

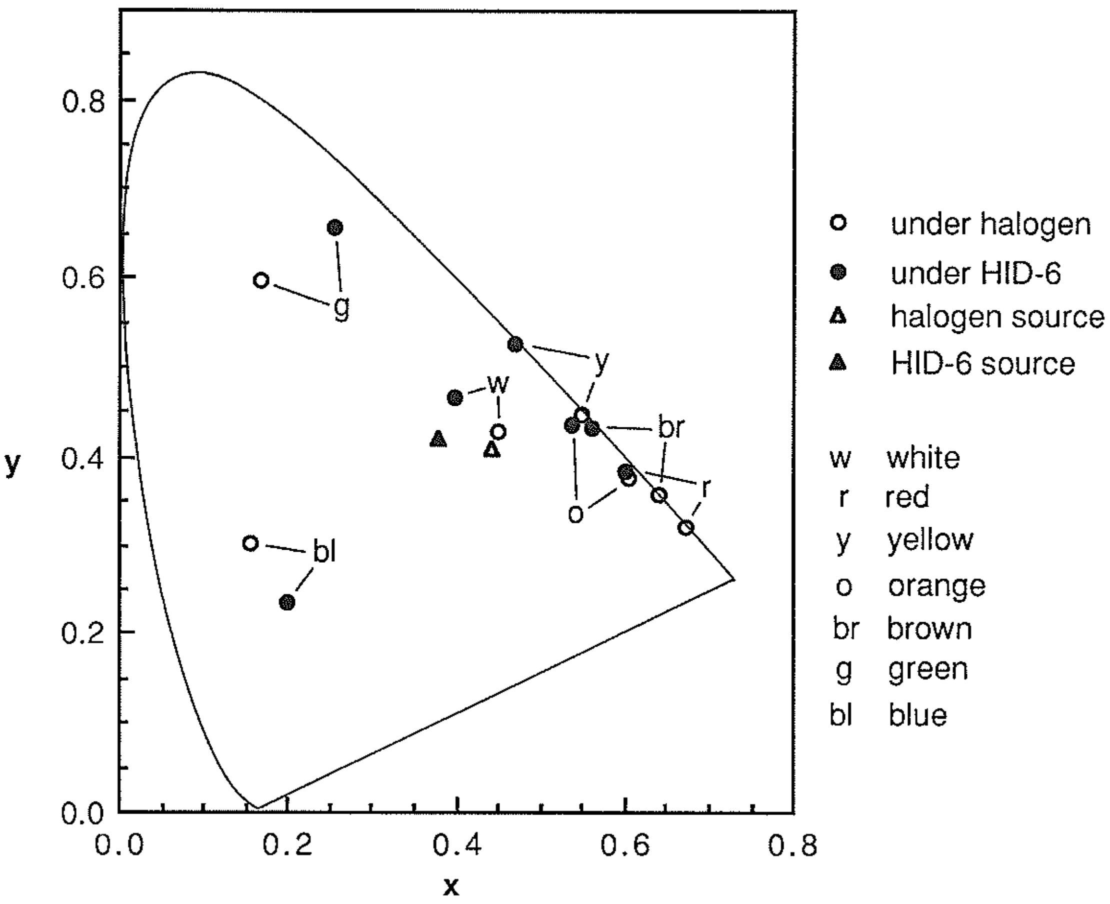


Figure 21. Chromaticities of the encapsulated-lens sign materials under HID-6.

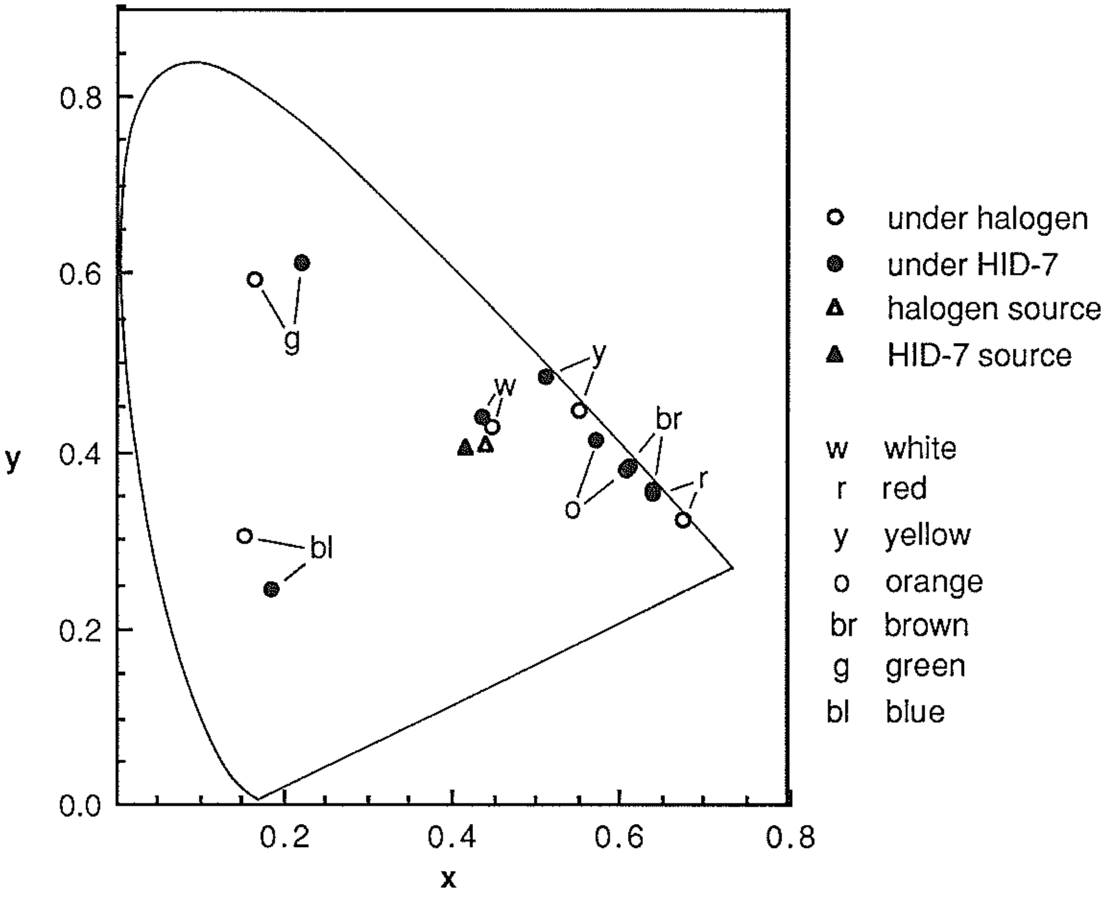


Figure 22. Chromaticities of the encapsulated-lens sign materials under HID-7.

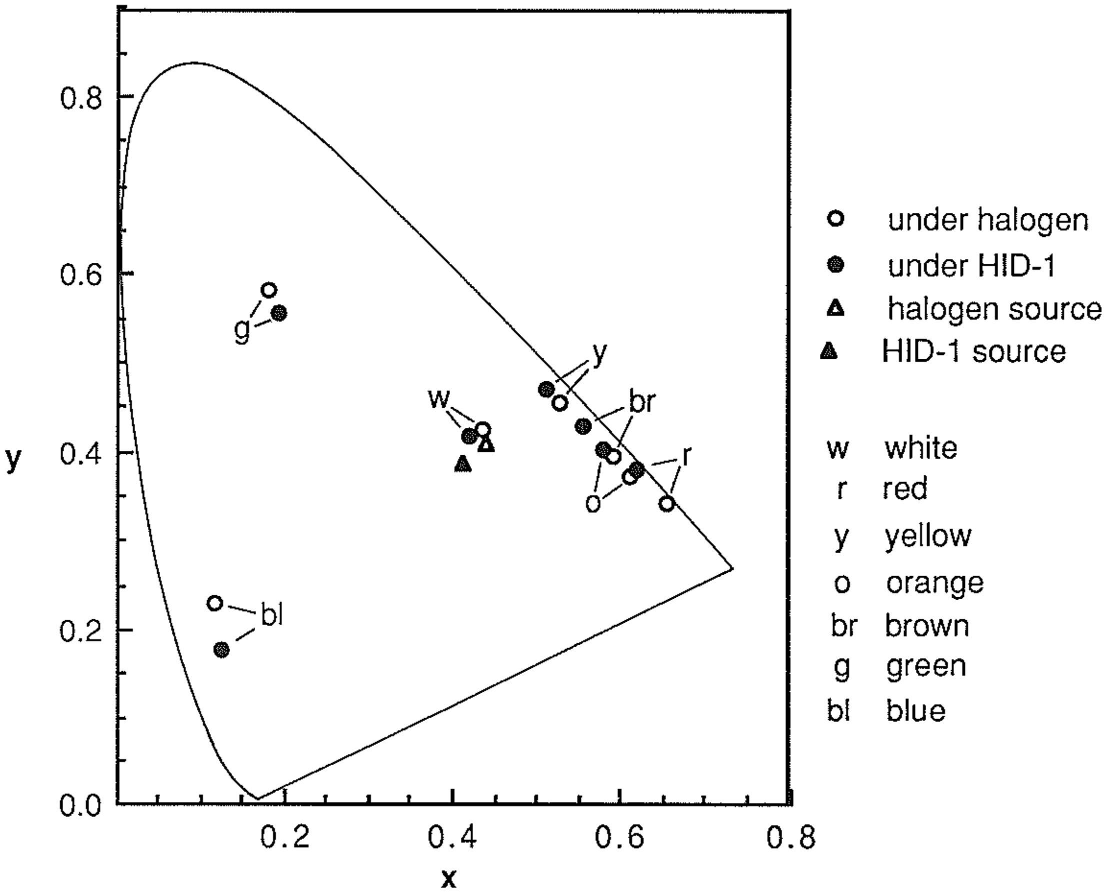


Figure 23. Chromaticities of the enclosed-lens sign materials under HID-1.

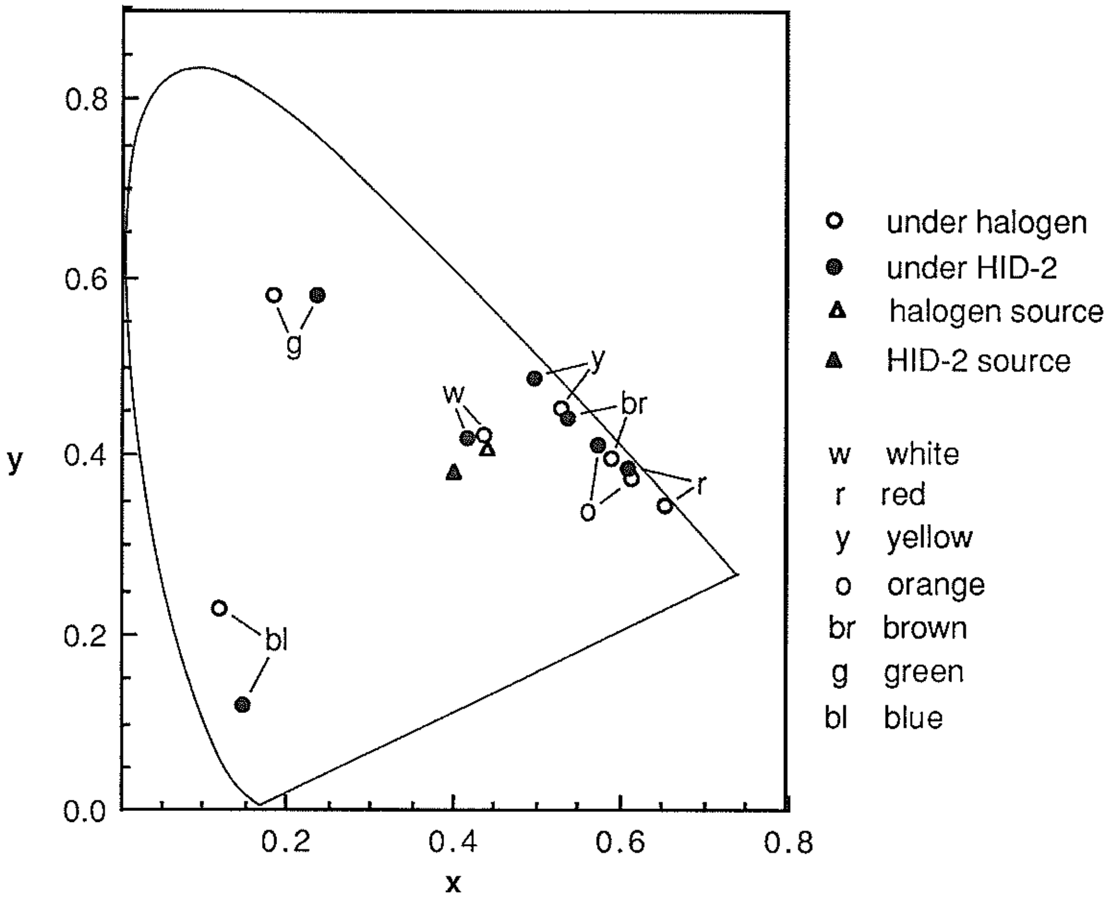


Figure 24. Chromaticities of the enclosed-lens sign materials under HID-2.

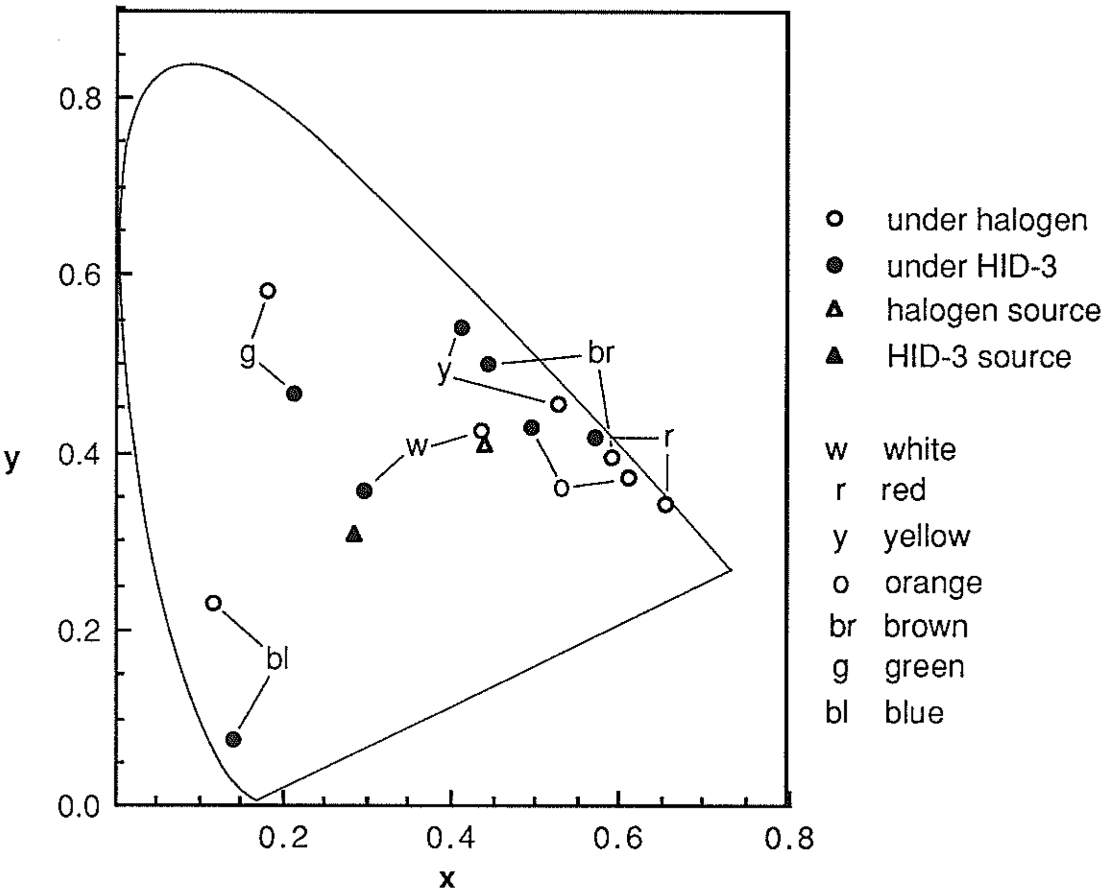
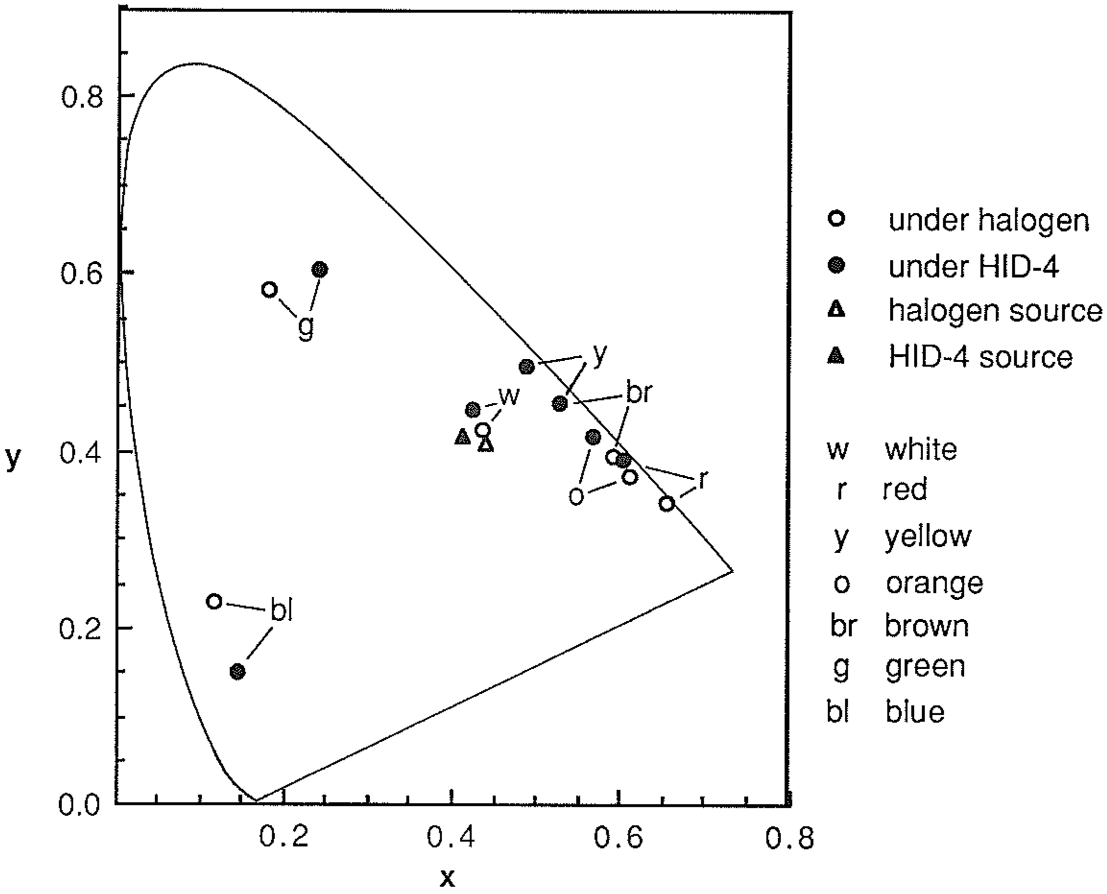


Figure 25. Chromaticities of the enclosed-lens sign materials under HID-3.



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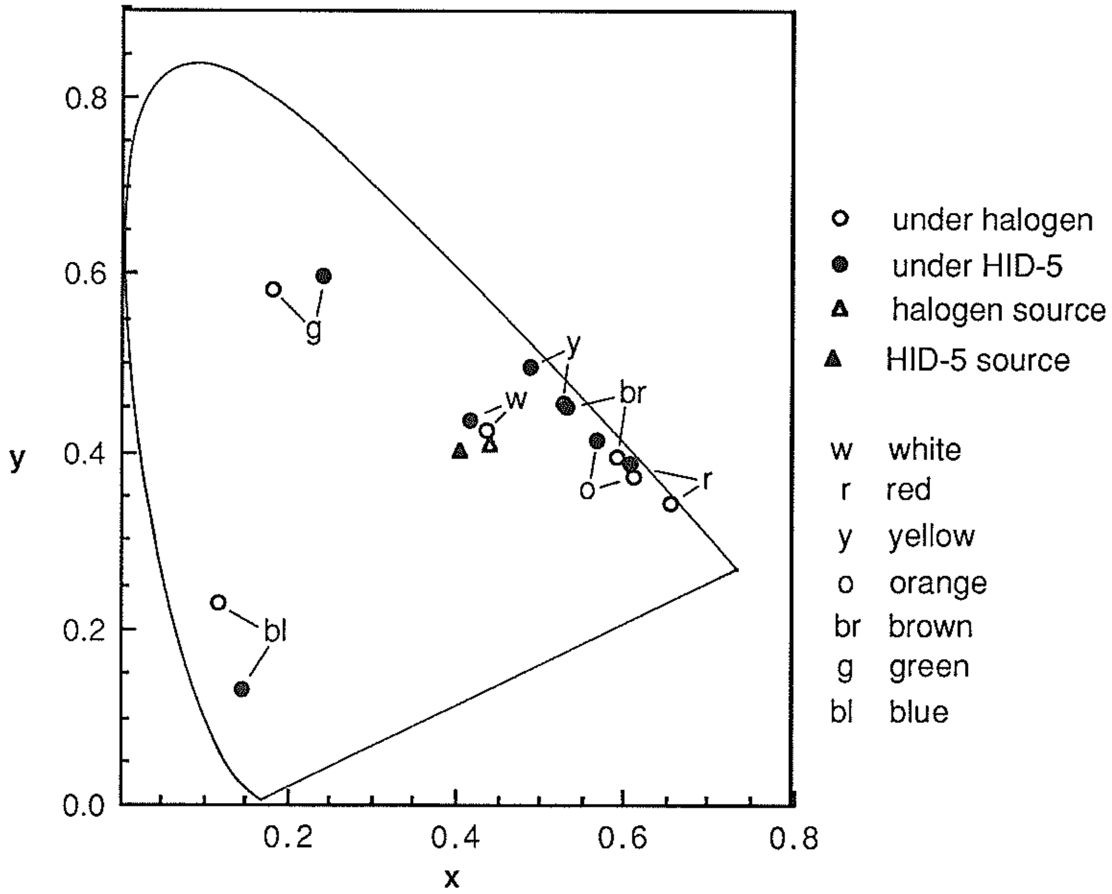

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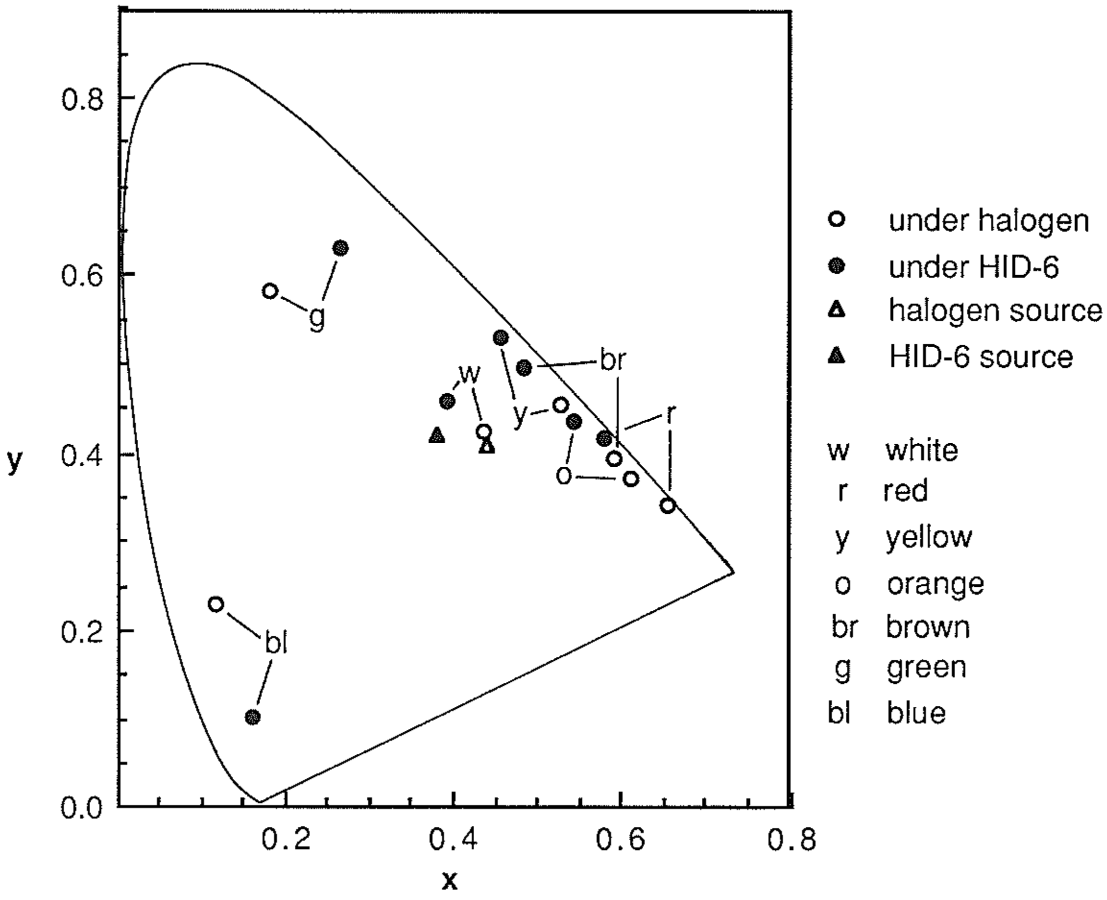

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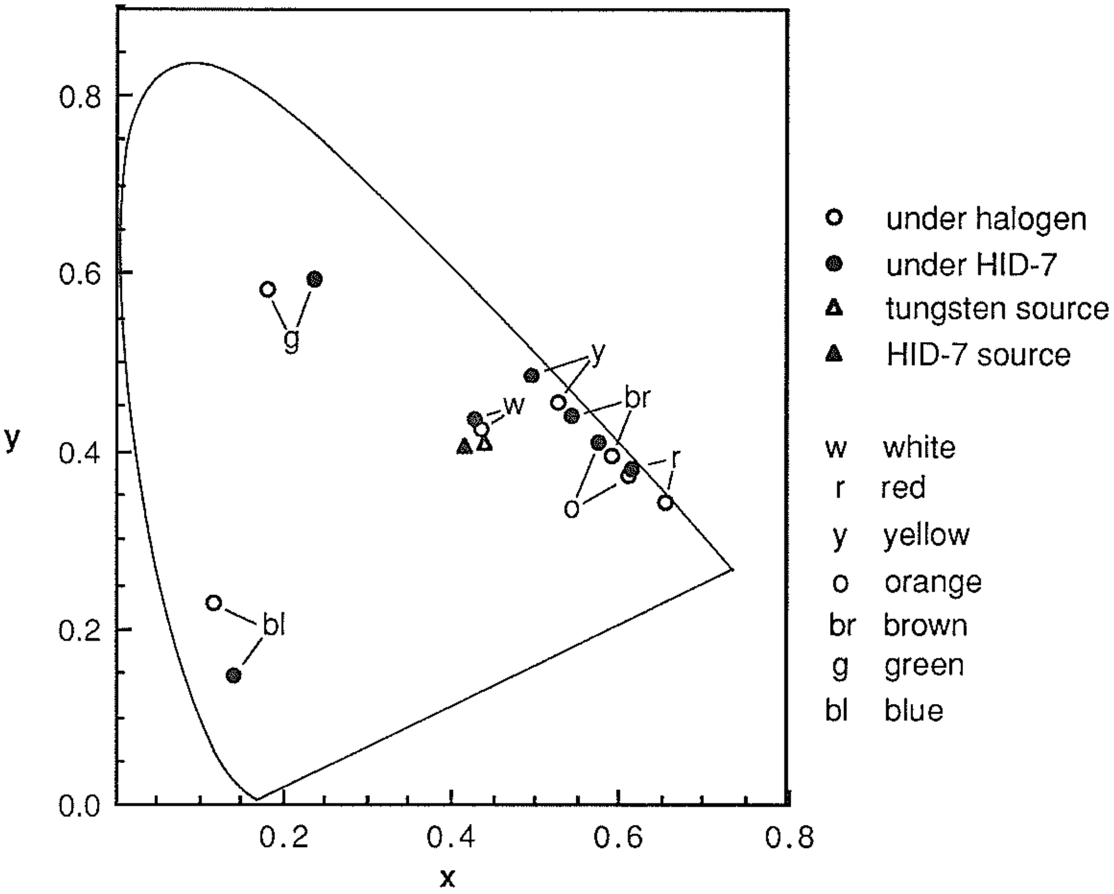

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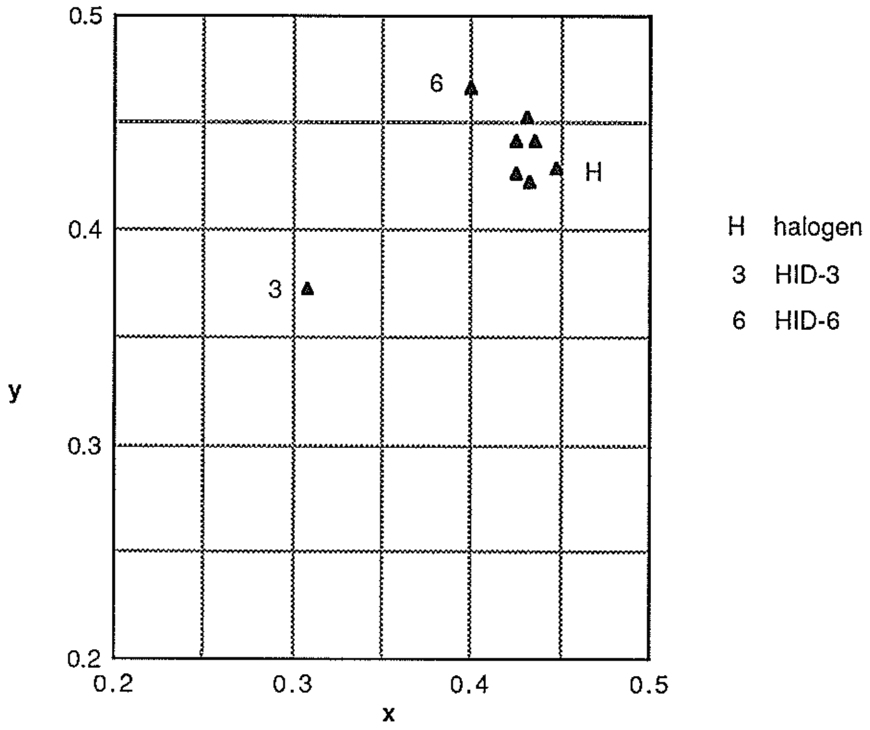
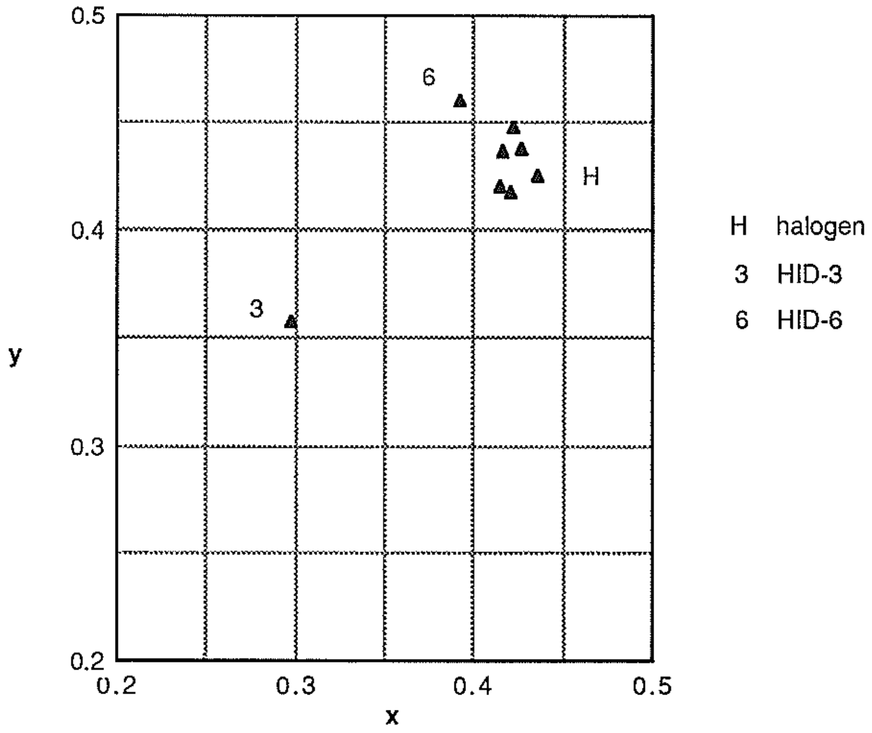


Figure 30. Chromaticities of the white encapsulated-lens sign materials.



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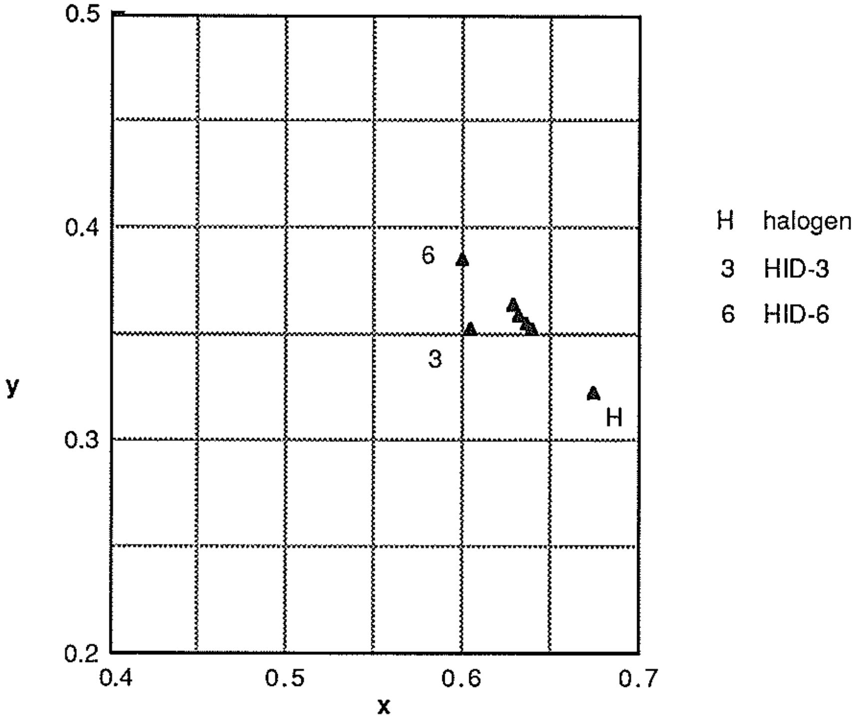

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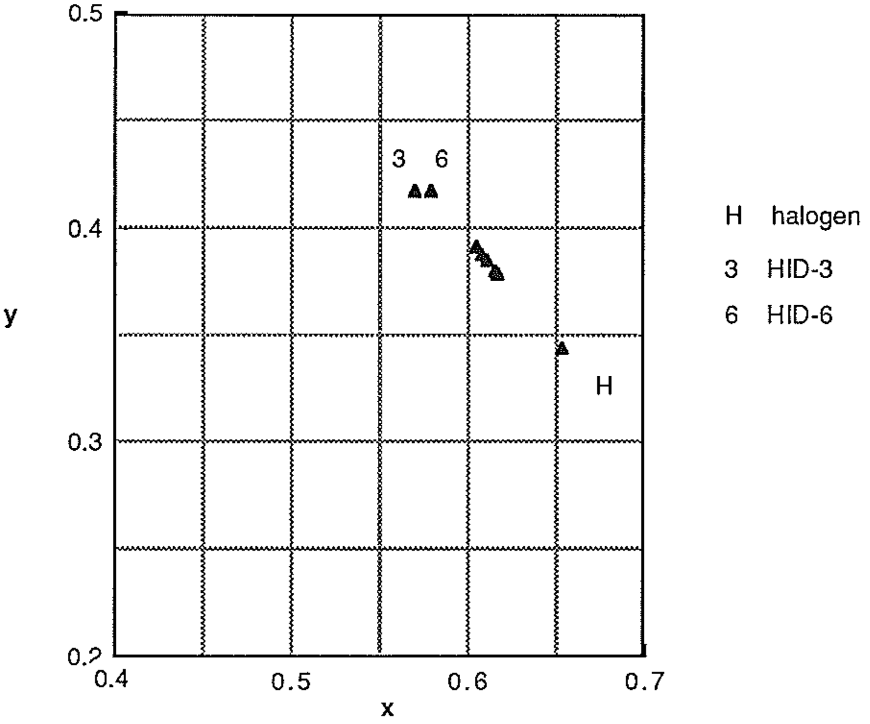

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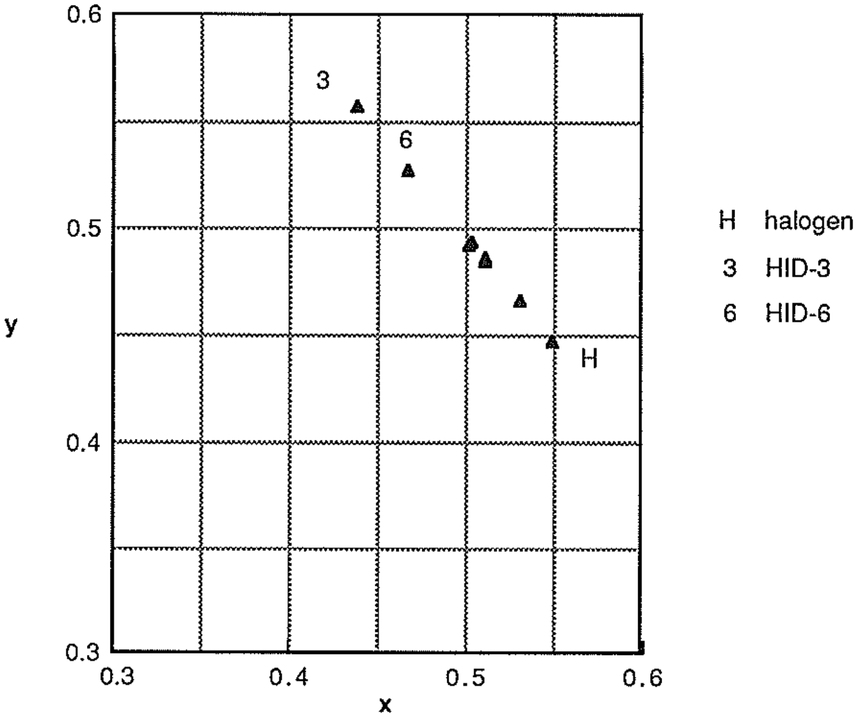
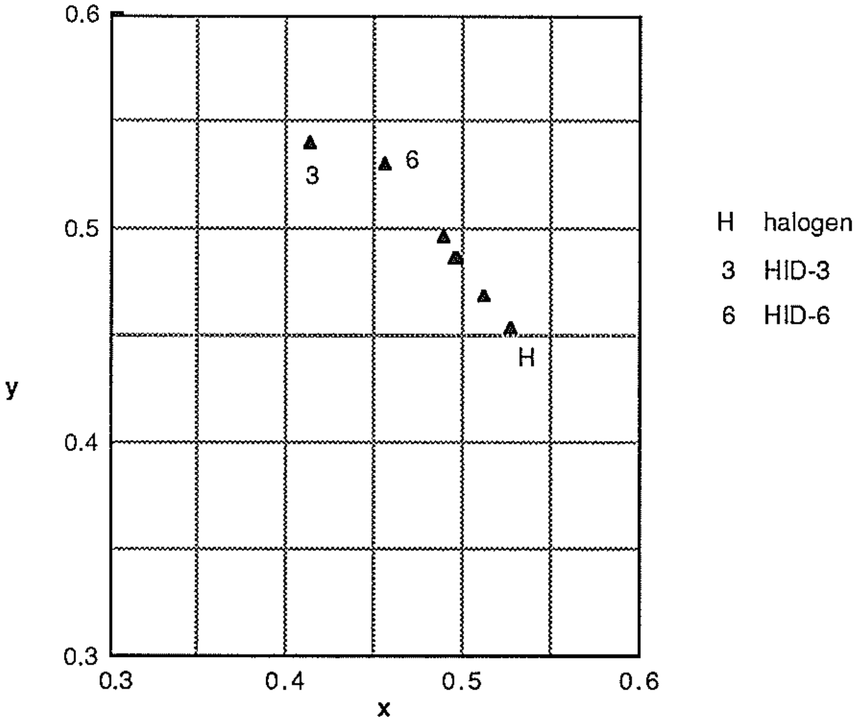


Figure 34. Chromaticities of the yellow encapsulated-lens sign materials.



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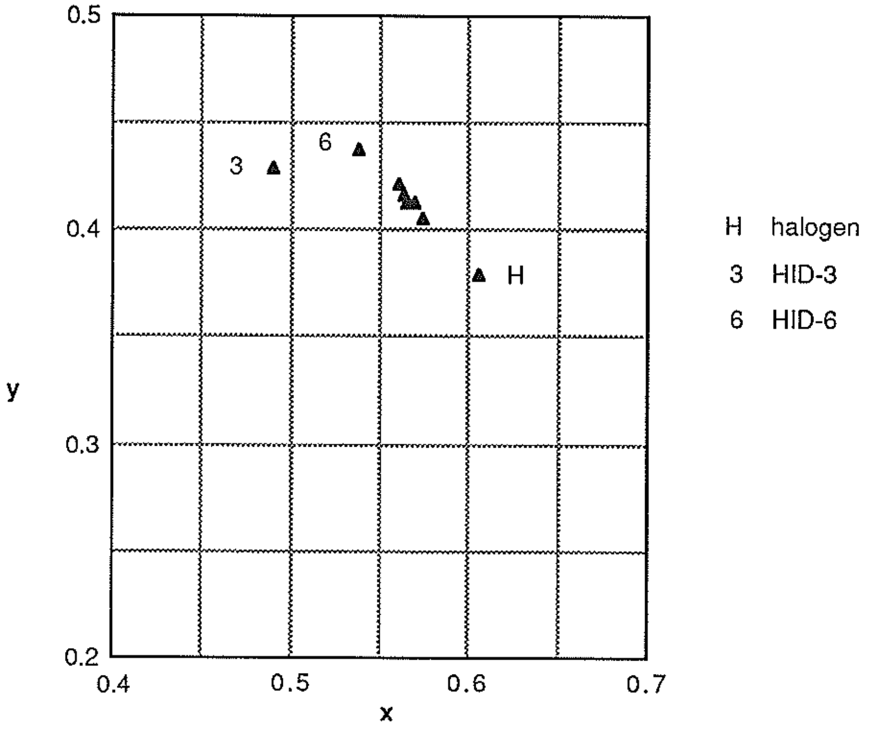


Figure 36. Chromaticities of the orange encapsulated-lens sign materials.

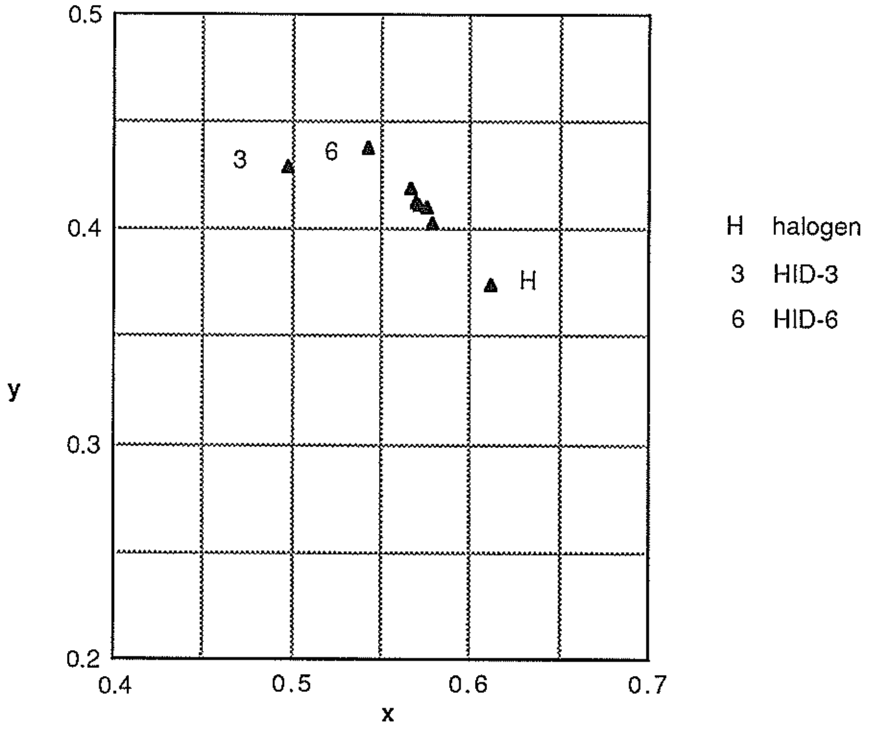


Figure 37. Chromaticities of the orange enclosed-lens sign materials.

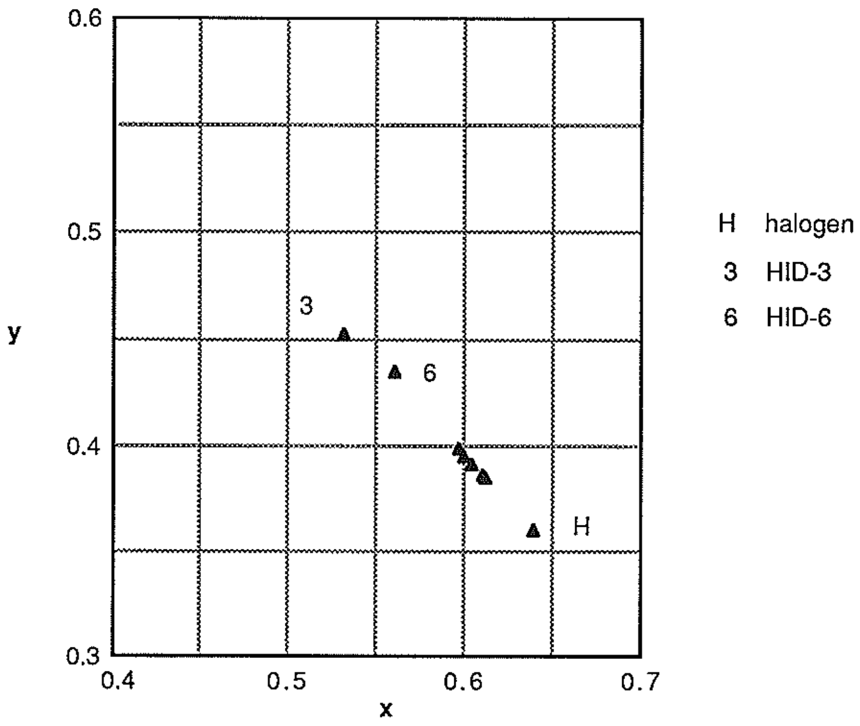


Figure 38. Chromaticities of the brown encapsulated-lens sign materials.

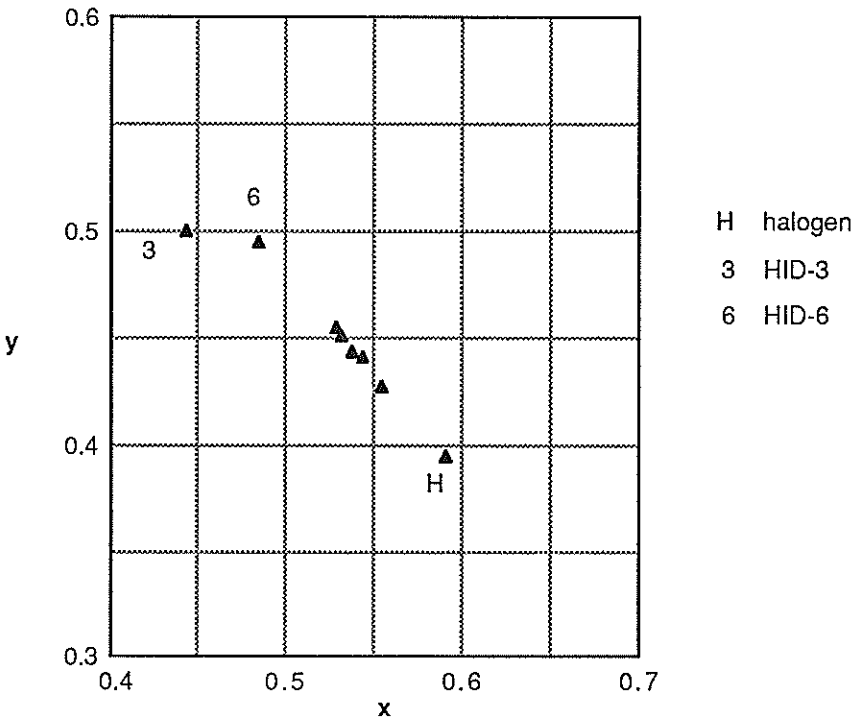
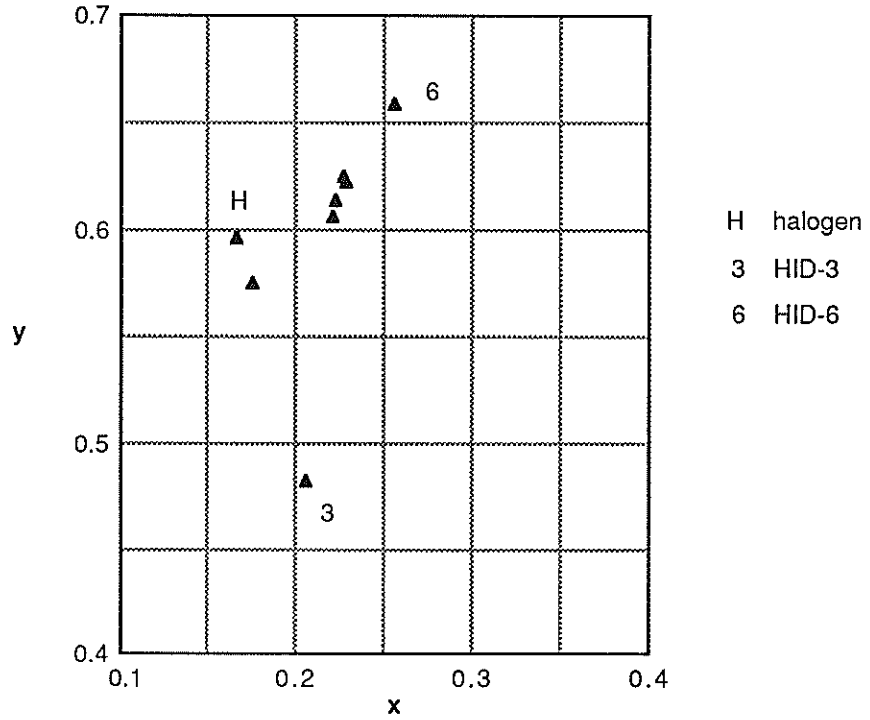


Figure 39. Chromaticities of the brown enclosed-lens sign materials.



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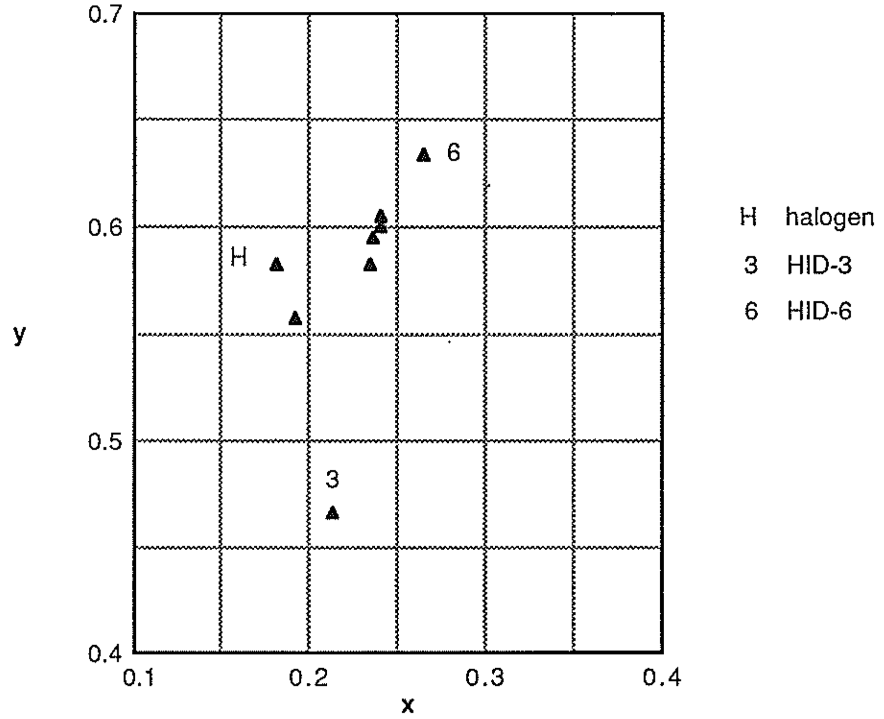

Figure 41. Chromaticities of the green enclosed-lens sign materials.

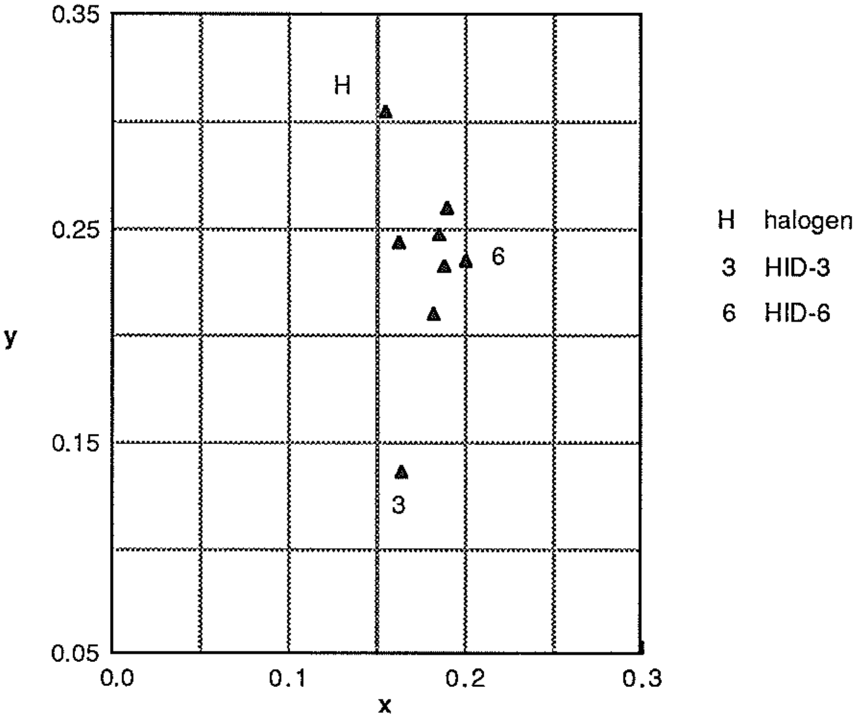

Figure 42. Chromaticities of the blue encapsulated-lens sign materials.

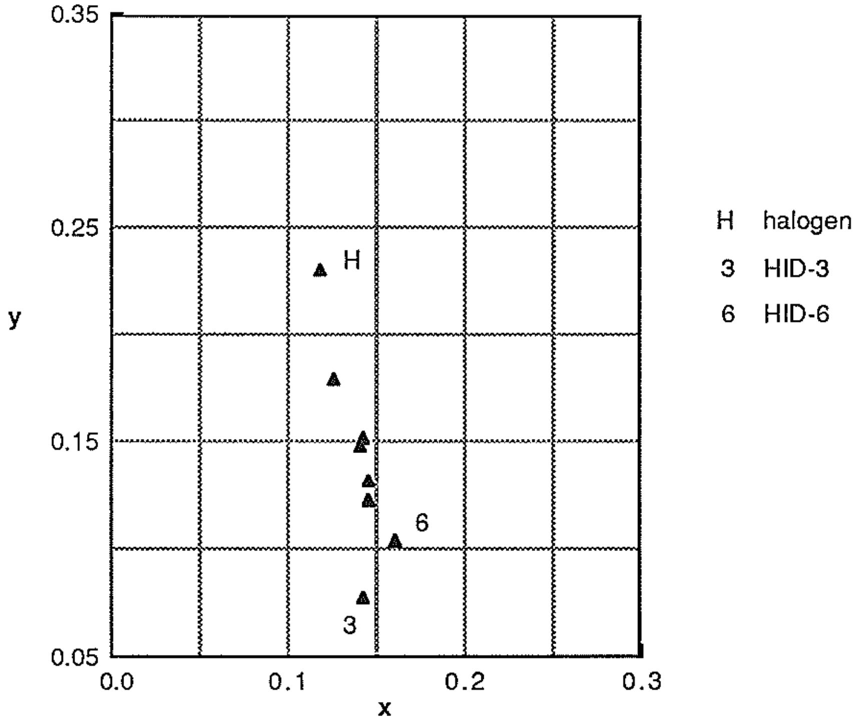

Figure 43. Chromaticities of the blue enclosed-lens sign materials.

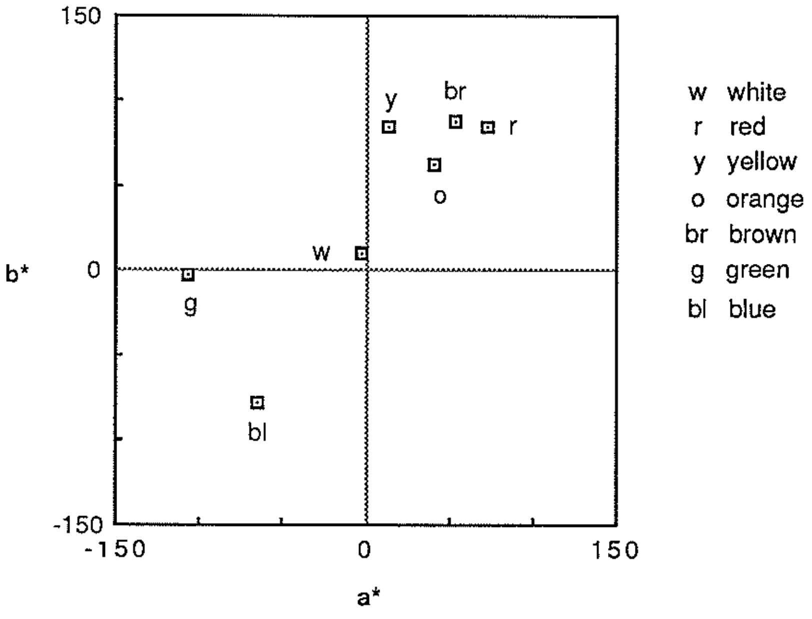

Figure 44. CIELAB chromaticities of encapsulated-lens sign materials under halogen.

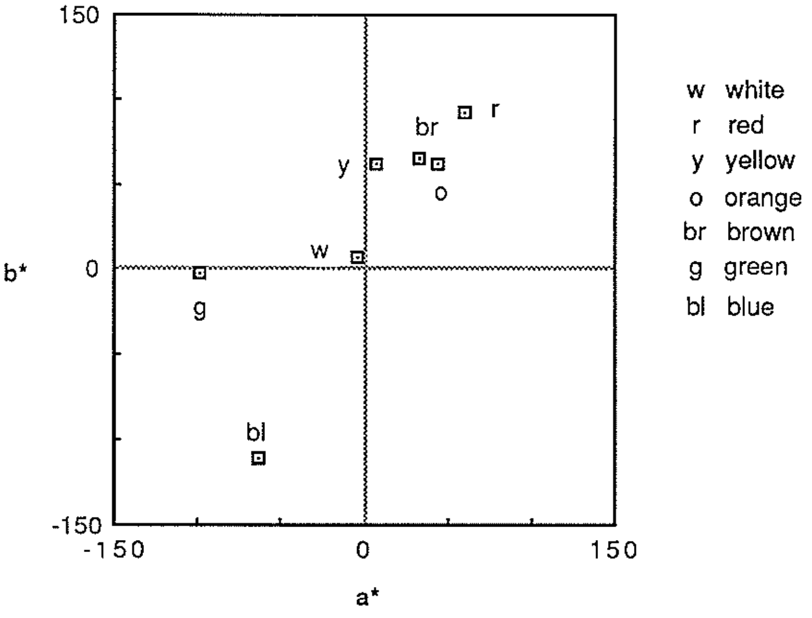

Figure 45. CIELAB chromaticities of enclosed-lens sign materials under halogen.

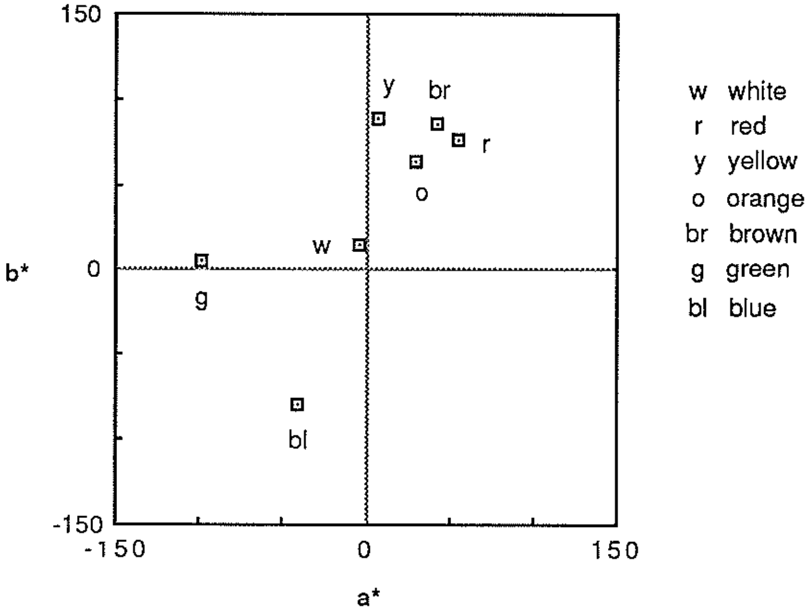

Figure 46. CIELAB chromaticities of encapsulated-lens sign materials under HID-1.

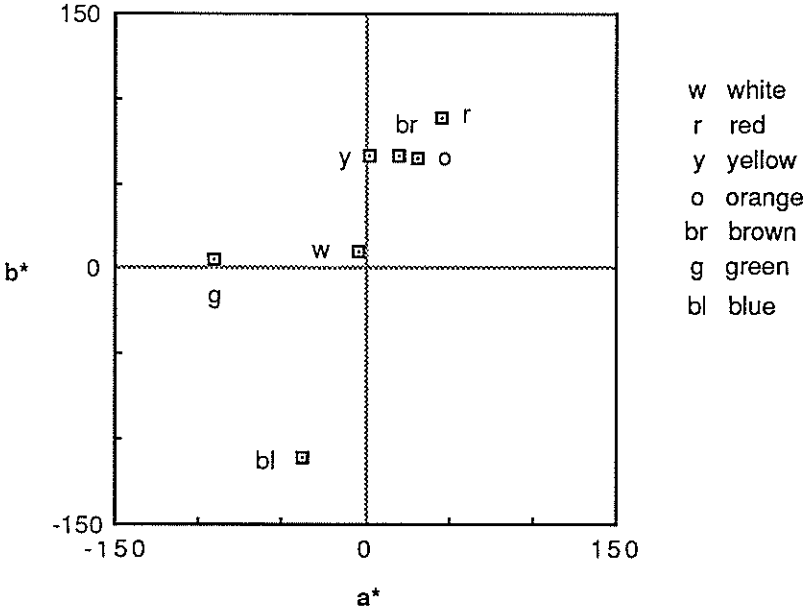

Figure 47. CIELAB chromaticities of enclosed-lens sign materials under HID-1.

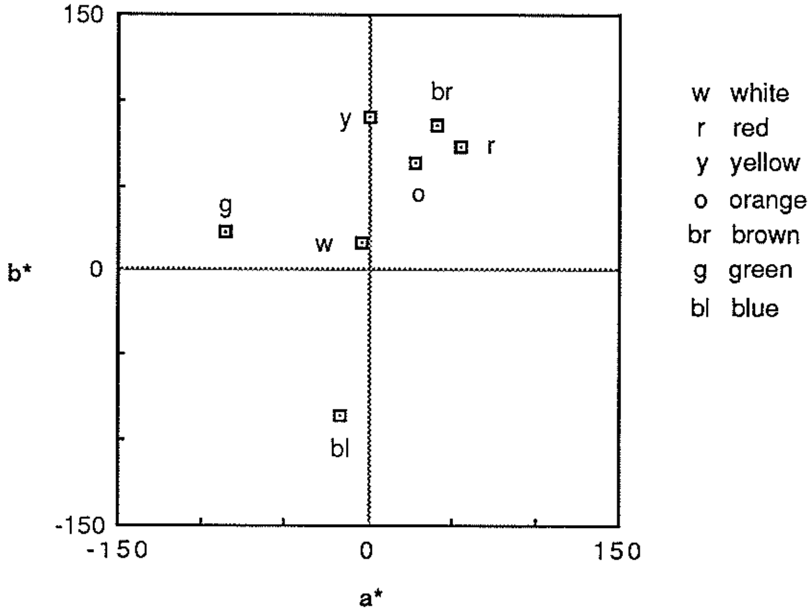

Figure 48. CIELAB chromaticities of encapsulated-lens sign materials under HID-2.

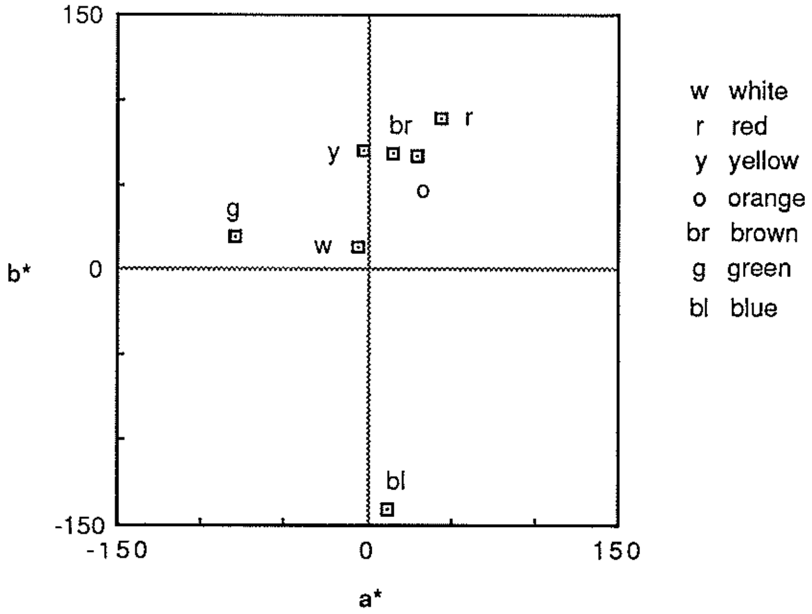

Figure 49. CIELAB chromaticities of enclosed-lens sign materials under HID-2.

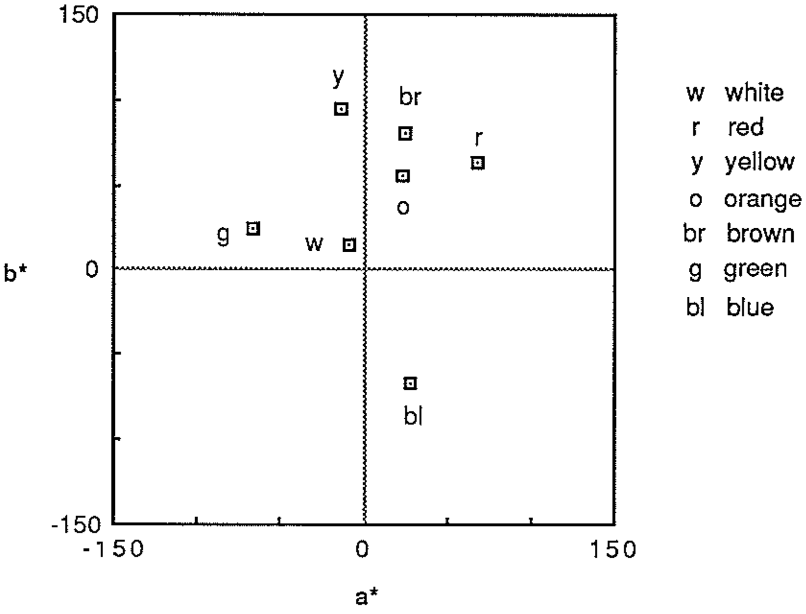

Figure 50. CIELAB chromaticities of encapsulated-lens sign materials under HID-3.

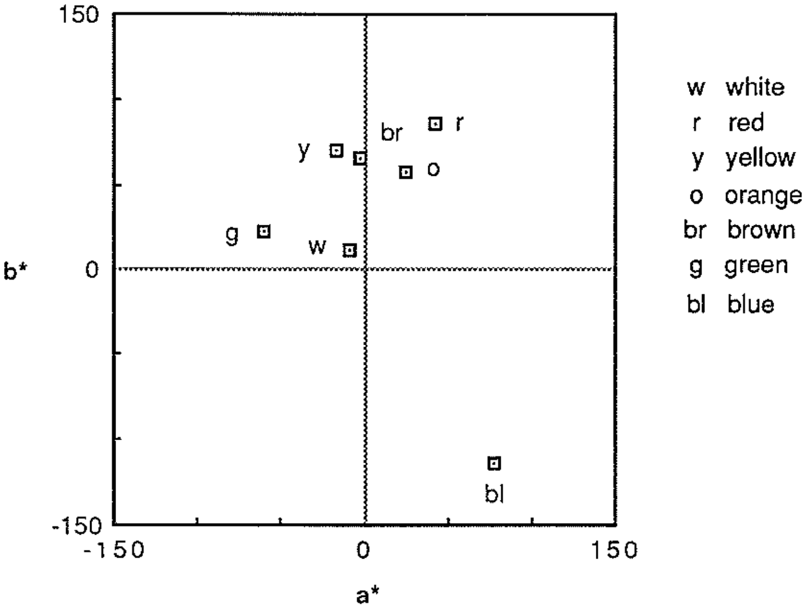

Figure 51. CIELAB chromaticities of enclosed-lens sign materials under HID-3.

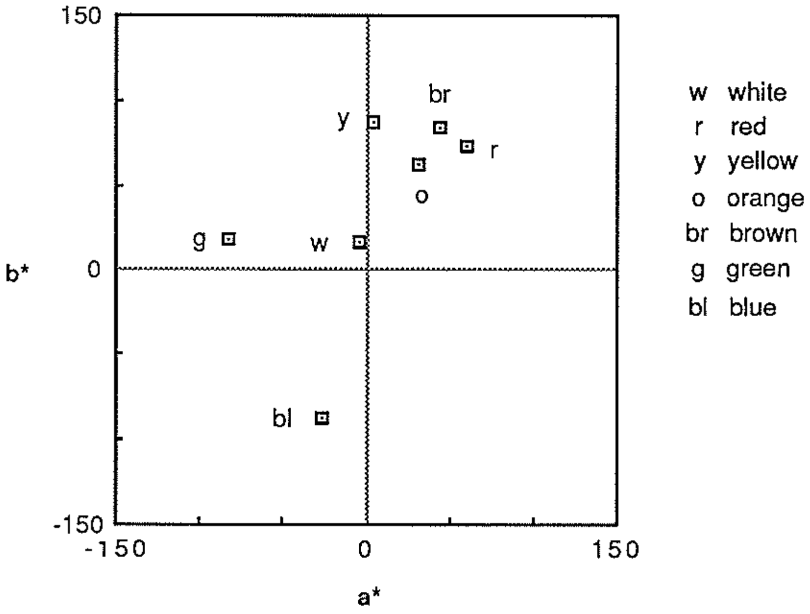

Figure 52. CIELAB chromaticities of encapsulated-lens sign materials under HID-4.

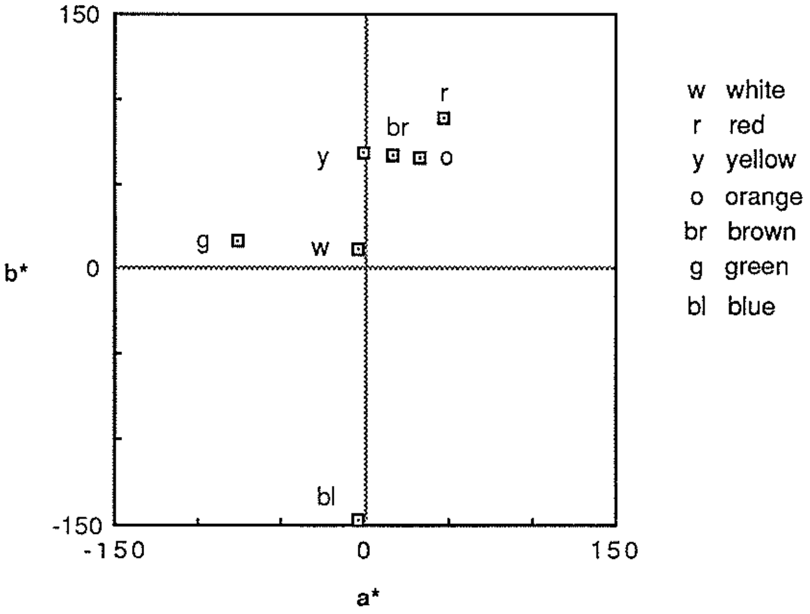

Figure 53. CIELAB chromaticities of enclosed-lens sign materials under HID-4.

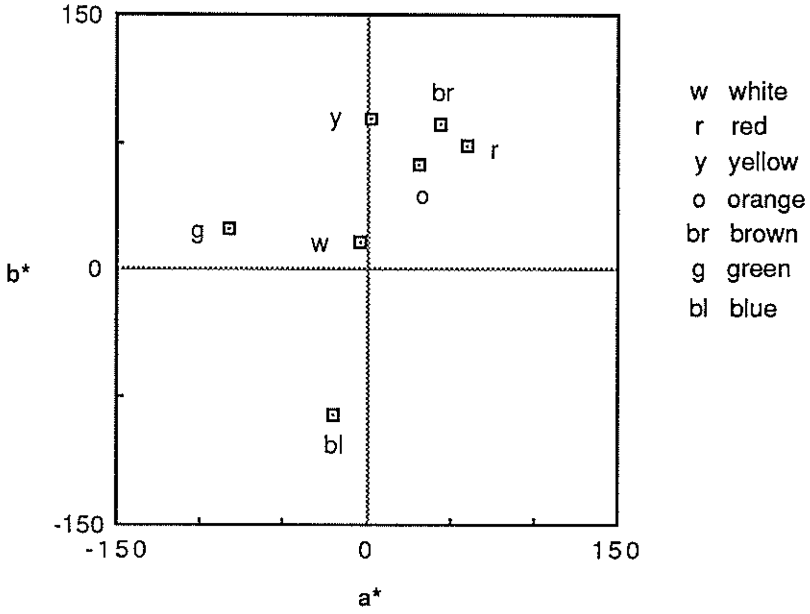

Figure 54. CIELAB chromaticities of encapsulated-lens sign materials under HID-5.

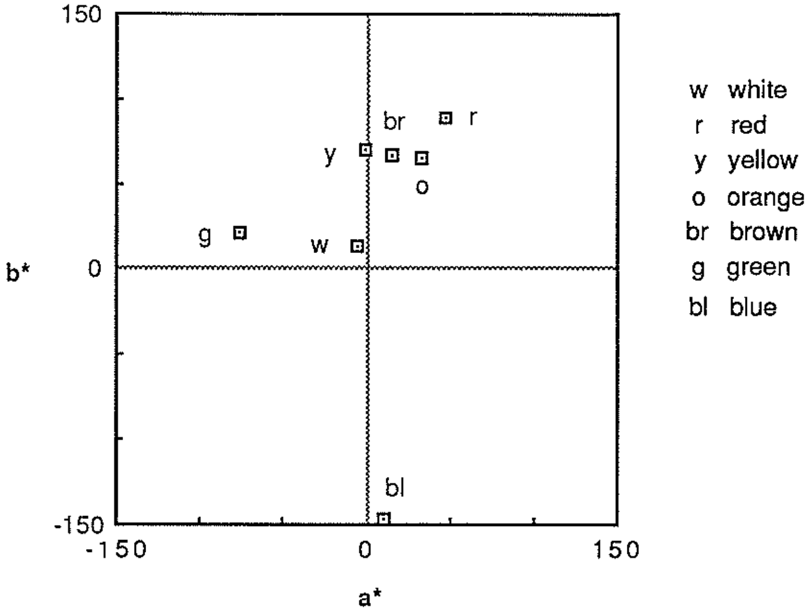

Figure 55. CIELAB chromaticities of enclosed-lens sign materials under HID-5.

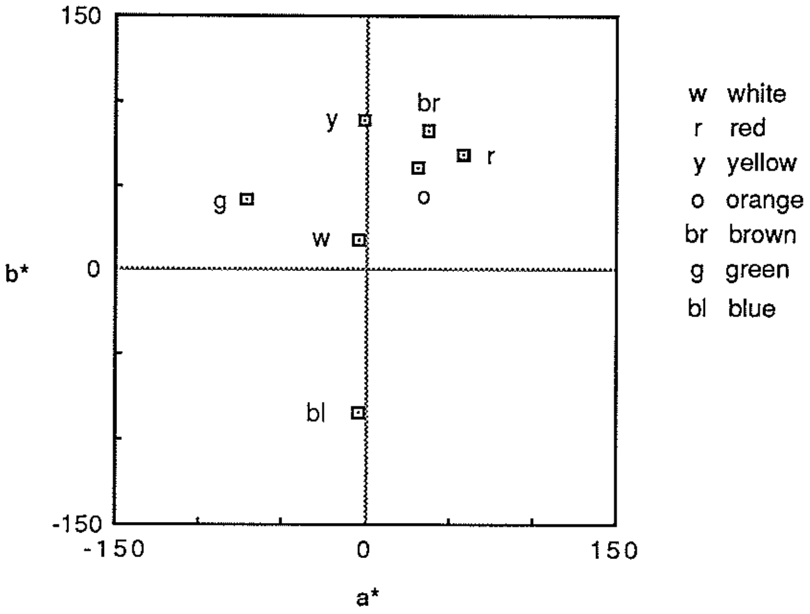

Figure 56. CIELAB chromaticities of encapsulated-lens sign materials under HID-6.

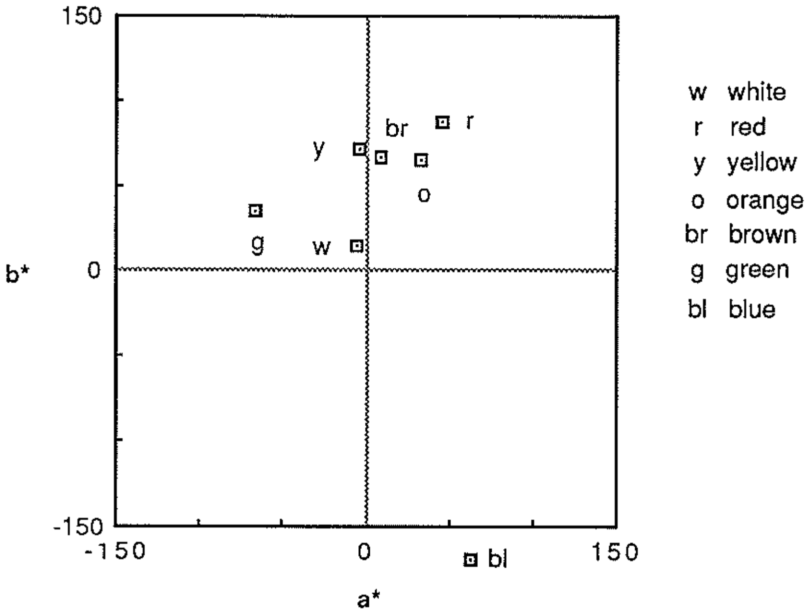

Figure 57. CIELAB chromaticities of enclosed-lens sign materials under HID-6.

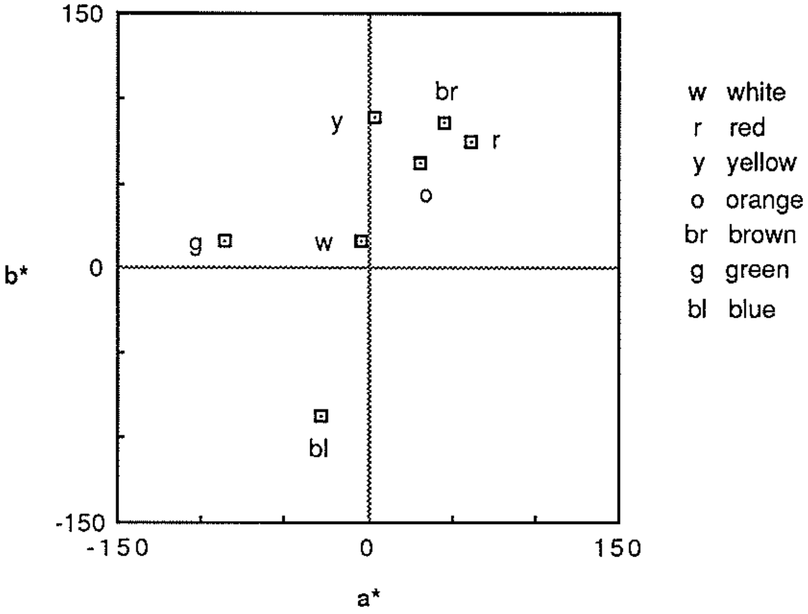

Figure 58. CIELAB chromaticities of encapsulated-lens sign materials under HID-7.

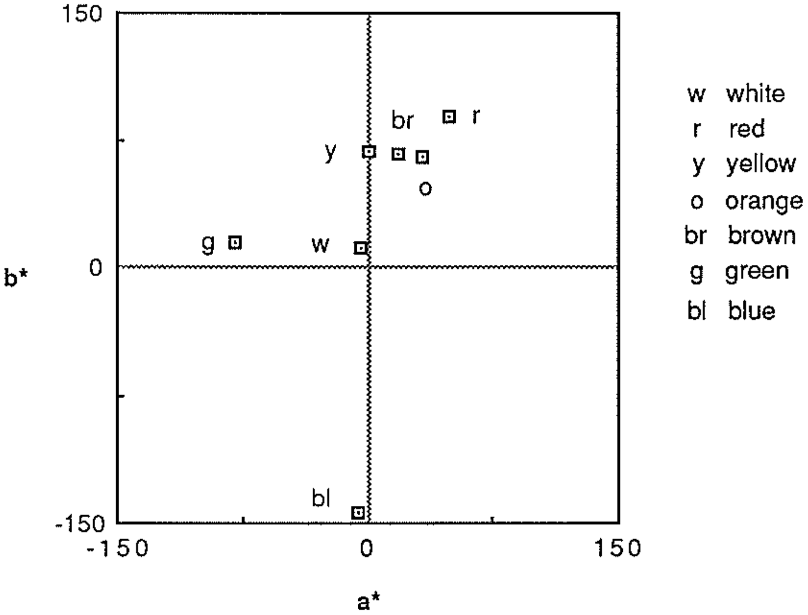

Figure 59. CIELAB chromaticities of enclosed-lens sign materials under HID-7.