

# Color Coordinates of Objects with Daylight Changes

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*Abstract:* Colorimetric changes were analyzed for a broad set of natural and artificial objects that were illuminated by daylight measured at different solar elevations on separate days, under diverse meteorologic conditions. The changes in  $L^*$ -,  $a^*$ -, and  $b^*$ -color coordinates of the objects, when illuminated with daylight at the maximum solar elevation and at twilight, normally exceeded 3 CIELAB units. However, color differences were not significant when evaluated during the middle hours of the day. Nor were significant differences found in the color of an object on different days, when evaluated during the middle hours. Color appearance attributes of the objects at intervals during the day were also calculated based on the CIECAM97s color appearance model, showing the trends with daylight changes. © 2002 Wiley Periodicals, Inc. *Col Res Appl*, 28, 25–35, 2003; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/col.10111

*Key words:* color constancy; daylight; object color

## INTRODUCTION

The analysis of the changes in the color of objects, natural and artificial, when observed under different natural-lighting conditions, is highly useful both from a purely colorimetric standpoint and from that of the research on color-vision mechanisms. Thus, in tasks of detection, recognition, and analysis of color under natural light, it is helpful to ascertain the colorimetric variations that can arise on changing the illumination on an object, and to determine whether these exceed certain fixed color tolerances or units of color difference. Also, knowing the real amount of these changes

could help the simulation and synthesis of changes in natural lighting on a recorded scene.

Color constancy is one of the aspects demanding the most effort in color-vision research.<sup>1</sup> For such a study, it is necessary to ascertain whether the visual system can compensate for the colorimetric changes occurring in objects when the illuminant undergoes changes, thereby maintaining constant the color appearance of those objects. Of the possible changes in illumination over an object, those due to variations in daylight are clearly fundamental to study.

In recent years, the color distribution of objects often found in natural scenes has been investigated in several works<sup>2–8</sup> by determining spectral reflectances with the use of different methods. These works demonstrate that the color distributions are restricted mainly within a certain area in the chromaticity diagram. Other studies<sup>9–12</sup> have analyzed the chromatic information provided by isolated objects commonly found in nature (such as leaves and tree bark, the ground, flowers). Although the spectral composition of the radiation illuminating these objects is known, few studies explore the variation in the color signals when the same object is illuminated by different daylight phases. Chiao *et al.*<sup>8</sup> obtained a set of color signals by multiplying the spectral reflectance of natural objects by six different daylight spectral power distributions (SPDs). They applied a PCA (principal components analysis) to represent them by a low-dimensional linear model. The authors found no significant differences among the illuminants in terms of the number of eigenvectors necessary for an adequate representation of the color signals by a linear model. For other reasons, Foster and Nascimento<sup>11</sup> generated random cone excitations from a set of Munsell surfaces and SPDs of skylight and daylight, and found that ratios of cone–photo-receptor excitations, which are produced by light from the different surfaces, remain almost invariant under illuminant changes. Thus, all the studies signal the importance of studying object color under daylight conditions.

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The main aim of our work was to determine the value of the changes generated in the color of objects under daylight shifts over the course of a day, and to compare the results of various days. For this, we took the reflectances of a group of natural and artificial objects (Vrhel *et al.*<sup>13</sup>), and the spectral data for daylight measured by our research group in a previous work (Hernández-Andrés *et al.*<sup>14</sup>). Our analysis involved the computation of chromaticity and luminance coordinates of the objects in the CIE-1931 and CIELAB color-representation systems, and the evaluation of color differences associated with the daylight variations. Also, color appearance was evaluated via the CIECAM97s color appearance model.

At first, it might be thought that these differences over a day should not be highly notable, especially if evaluated during the middle hours of the day, given that the variations in daylight<sup>14</sup> found in this period are not great. However, the scientific conclusions can be considered definitive only when supported by experiments, and, in our case, this will be done when the color differences are calculated and evaluated.

In addition, we seek to establish how color differences increase when comparisons are made of the color coordinates of objects seen under extreme illumination of the day, namely, the highest solar elevation and twilight. Other aspects to evaluate include whether the values of the color differences change with the perceptual attributes that define color, and how atmospheric conditions influence the color coordinates of the same object—that is, the possible variations on being evaluated on different days.

## OBJECTS AND ILLUMINANTS

As indicated earlier, the reflectances of objects used were those of Vrhel *et al.*,<sup>13</sup> totaling 173, involving both natural and artificial objects measured between 400 and 700 nm. The set of objects selected expands a color gamut similar to that reported by Burton and Moorhead,<sup>3</sup> and by Webster and Mollon<sup>5</sup> on natural scenes.

With respect to the illuminants, we used a broad group of daylight data (hemispherical daylight that can include direct sunlight) from a measurement campaign performed by

members of our laboratory in the city of Granada (Spain).<sup>14</sup> All the measurements refer to an urban but nonindustrial area (latitude: 37°11' N, altitude: 680 m). From the complete set of measurements, we selected those belonging to 3 clear days, 2 cloudy days, and 1 day of mixed weather conditions. In addition, we included a day in which the daylight measurements had special characteristics: an increase in the yellow-reddish content of the light measured, due to the high presence of atmospheric dust, especially during the first few hours of the day. The measurements of each day were made from sunrise to sunset, including twilight, with a Licor 1800 spectroradiometer, with a spectral resolution of 5 nm, between 300 and 1100 nm. The magnitude measured was the overall spectral irradiance on a horizontal surface. More details of the measurements can be found in Hernández-Andrés *et al.*<sup>14</sup> Table I lists the global atmospheric conditions and the total number of measurements of daylight for each day.

By including twilight, we are considering not only photopic illumination levels but also mesopic ones. The calculated luminances for a white surface range from 50 to 25,000 cd/m<sup>2</sup>, indicating that the simulated observation of certain color objects at sunrise and sunset remains within the mesopic level, near the photopic. Our calculation of color coordinates did not take into account variations in the spectral sensitivity of color-vision mechanisms according to the level of illumination. In any case, the great majority of the calculations fell within the photopic level, and only in a few cases at twilight was the level mesopic but very close to photopic. To include the twilight data provides important information on color variation of objects, because this time of the day registers the greatest variations in daylight SPDs.<sup>14</sup>

## RESULTS

### Colorimetric Variations

Throughout our work, we have obtained the color signal corresponding to each pair of object + illuminant, multiplying the spectral reflectance of the object by the spectral irradiance measured while considering the objects to be

TABLE I. Set of daylight data measured in Granada, Spain. for each day, the total number of measurements of daylight is specified (fourth column).

Date	Day label	Atmospheric conditions	Number of measurements	(x, y) Maximum elevation	(x, y) Twilight
2 Aug 1996	cl1	Completely clear day	19	(0.3264, 0.3382)	(0.2761, 0.2981)
10 Feb 1997	cl2	Completely clear day, with high visibility	14	(0.3298, 0.3404)	(0.2822, 0.3004)
8 Sept 1997	cl3	Completely clear day	16	(0.3262, 0.3377)	(0.2833, 0.3029)
7 Apr 1997	ov1	Completely overcast day, with little rain	13	(0.3236, 0.3360)	(0.2616, 0.2767)
10 Jan 1997	ov2	Completely overcast day, with fog	12	(0.3198, 0.3336)	(0.2511, 0.2657)
22 Sept 1997	mix	Partly cloudy	17	(0.3269, 0.3387)	(0.2821, 0.3022)
15 Aug 1996	dst	Scattered clouds, with fog and atmospheric dust	13	(0.3220, 0.3341)	(0.3932, 0.3896)

The CIE1931 chromaticity coordinates of daylight at “extreme” conditions are also shown: the measurement at maximum solar elevation (fifth column) and the measurement during twilight (sixth column).

Lambertian. Thus, on calculating the luminance of each object, or the tristimulus value  $Y$  in the CIE-1931 system, we assumed that the spectral radiance  $L_\lambda$  of the object was related with the spectral irradiance from the illuminant  $E_\lambda$  over the object, through the expression  $\rho_\lambda E_\lambda = \pi L_\lambda$ , where  $\rho_\lambda$  is the spectral reflectance of the object.

For the calculations of  $L^*$ -,  $a^*$ - and  $b^*$ -color coordinates, we needed to fix a reference white. We considered as such the color signal derived from a perfectly white object—that is, with a reflectance of value 1 for all the wavelengths of the visible spectrum—illuminated by the corresponding daylight. Therefore, the tristimulus values of white object changes with the illuminant.

Table II shows, as an example, the results for a purple object during the different daylight phases over a complete day. These suggest that colorimetric variations were minor when the middle hours of the day were compared together, whereas when these measurements were compared to twilight values, significant differences arose. As might be expected, variations in chromaticity coordinates of an object in the CIE-1931 system, from the maximum solar elevation to twilight, followed the tendency shown by the daylight itself—that is, the main variation in the yellow-blue direction (Hernández-Andrés *et al.*<sup>14</sup>), with no differences between sunrise and sunset.

The color coordinates in the CIELAB system ( $L^*$ -,  $a^*$ -,  $b^*$ -hue and chroma) behaved differently. In the case of the purple object in Table II, we noted a major variation in the coordinate  $a^*$ , this being in the red-green direction of the CIELAB  $a^*$ ,  $b^*$  diagram, with a tendency toward red on passing from midday to twilight. The coordinate  $b^*$  hardly changed; meanwhile, the variation of  $L^*$  was less notable over the day, whereas variations were in fact noted in the hue and chroma values.

When we extended our study to the complete set of objects and days, the variations found for  $L^*$  continued to be

scarcely significant. This is evaluated quantitatively in the section on color differences, where we calculate the color and chromaticity differences associated with illumination changes. This result indicates that the variable  $L^*$ , related to the perceptual attribute lightness, hardly varied with object illumination, both for different atmospheric conditions and for different hours of the day. This result could be expected since the definition of  $L^*$  depends on the ratio between  $Y$  values for the object and the white under the illuminant. In our case, the changes in the illuminant mainly affect the relative content in the long- and short-wavelength parts of the SPD (see Fig. 1), which have less influence on the calculation of the tristimulus value  $Y$ . Then, for each illuminant condition, the ratio between  $Y$  values varies slightly.

With respect to the variables  $a^*$  and  $b^*$  in Fig. 2, we show, in the CIELAB  $a^*$ ,  $b^*$  diagram, segments that connect the coordinates found at the maximum solar elevation and at twilight for the entire set of objects on the same day. We found, first of all, that the variations in the  $a^*$ ,  $b^*$  coordinates were more significant the greater the chroma of the objects (farther distance from the origin). The differences for the achromatic objects or near them were clearly less than for objects of greater chroma.

Second, the direction of the variation was defined almost according to whether we were dealing with objects with coordinates situated in the upper or lower part of the diagram; that is, those in the upper part, except for some of high  $a^*$  values, showed a clear trend to diminish the  $a^*$  value toward twilight, whereas those of the lower zone tended toward higher  $a^*$  values. If we expressed this in terms of appearance, the trends would be to diminish or to augment the red content, respectively. Another way to express this would be that the variations are given in the red-green direction, depending on the relative yellow-blue content in the object's color.

With regard to hue and chroma, we find that for the

TABLE II. CIExy chromaticity coordinates and CIELAB values for a purple object on a clear day (cl1).

Solar elevation (°)	$x_d$	$y_d$	$x$	$y$	$a^*$	$b^*$	$L^*$	$H$	$C$
0.4	0.2795	0.3006	0.2451	0.1896	17.34	-17.18	18.65	315.26	24.41
1.7	0.2826	0.3028	0.2474	0.1914	17.10	-17.25	18.63	314.76	24.29
3.2	0.2844	0.3044	0.2485	0.1926	16.94	-17.32	18.60	314.36	24.22
4.3	0.2849	0.3048	0.2486	0.1928	16.88	-17.36	18.58	314.19	24.21
5.5	0.2992	0.3149	0.2623	0.2033	16.00	-17.29	18.59	312.79	23.56
6.8	0.3061	0.3202	0.2688	0.2087	15.57	-17.27	18.58	312.03	23.25
21.6	0.3308	0.3452	0.2935	0.2346	13.81	-17.21	18.49	308.75	22.06
32.5	0.3310	0.3414	0.2928	0.2308	13.95	-17.31	18.50	308.88	22.23
47.5	0.3288	0.3398	0.2903	0.2290	14.02	-17.32	18.50	308.99	22.28
59.2	0.3288	0.3402	0.2903	0.2294	13.98	-17.30	18.49	308.93	22.24
68.9	0.3264	0.3382	0.2878	0.2271	14.11	-17.34	18.49	309.15	22.35
50.1	0.3283	0.3397	0.2899	0.2290	14.01	-17.29	18.50	309.01	22.25
39.1	0.3295	0.3413	0.2915	0.2308	13.91	-17.24	18.50	308.91	22.15
21.8	0.3288	0.3409	0.2912	0.2306	13.98	-17.17	18.52	309.15	22.14
10.0	0.3169	0.3309	0.2795	0.2197	14.78	-17.21	18.55	310.65	22.68
5.4	0.3107	0.3217	0.2741	0.2157	15.18	-17.16	18.57	311.48	22.91
3.7	0.3043	0.3216	0.2681	0.2102	15.68	-17.15	18.60	312.32	23.20
1.9	0.2984	0.3154	0.2629	0.2044	16.10	-17.11	18.64	313.25	23.50
-0.2	0.2761	0.2981	0.2423	0.1875	17.56	-17.13	18.67	315.71	24.53

( $x_d, y_d$ ) are chromaticity coordinates of daylight at each solar elevation.

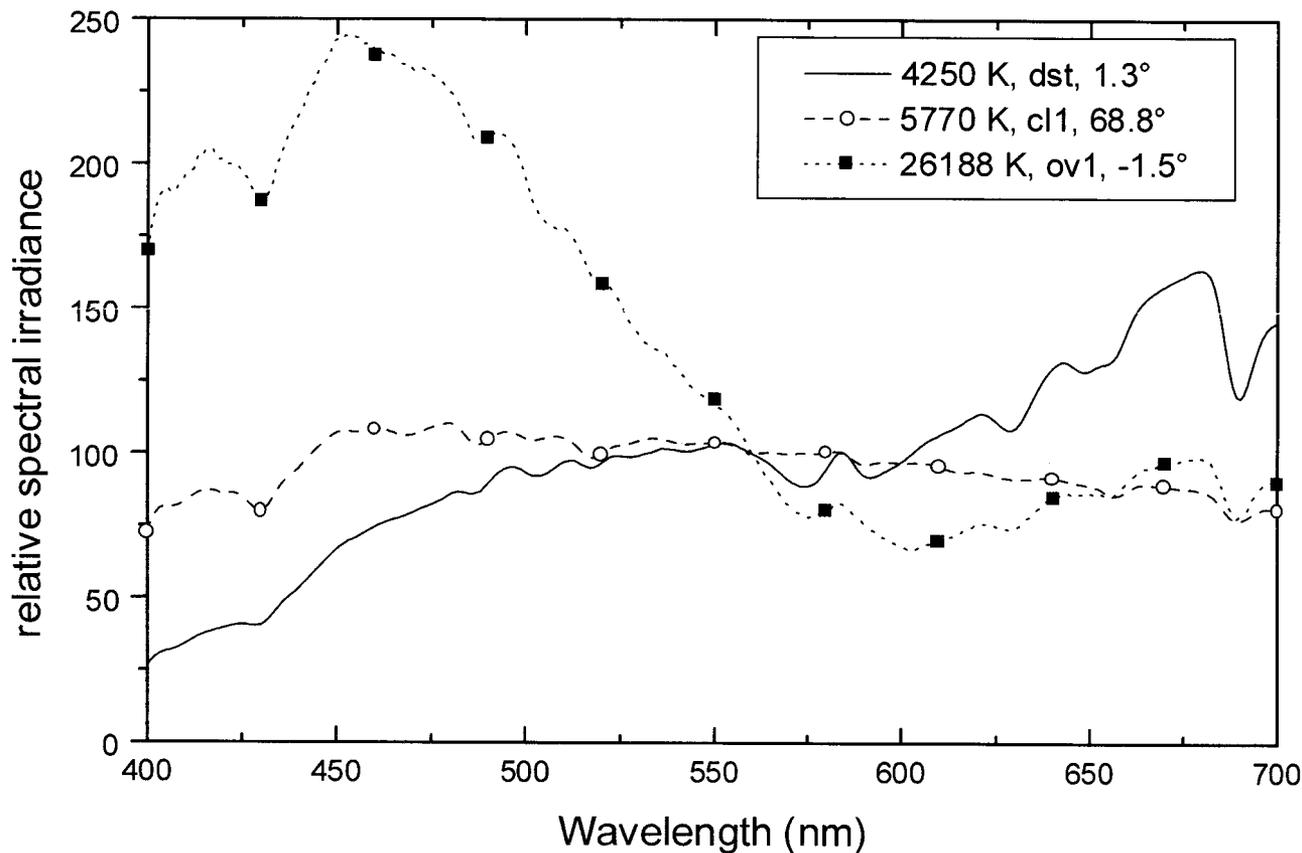


FIG. 1. Relative spectral irradiance, normalized at 560 nm, for three Granada spectral daylight SPDs. We include the correlated color temperature (CCT) of each SPD, the day of measurement, and the corresponding solar elevation angle.

objects represented close to the  $a^*$  and  $b^*$  axes, the main variations appeared in hue, with chroma remaining practically constant. On the other hand, for objects far from the axis, the variations in chroma were notable.

Due to the definition of  $a^*$  and  $b^*$  values, variations in the yellow-blue content of daylight, Fig. 1, can lead to important changes in their values, especially for high values of either of them. Thus, the ratio between  $X$  values for the object and the white, which appears in the  $a^*$  value definition, can be influenced greatly by variations in the short- and long-wavelength content of the illuminant. The same occurs in the  $Z$  ratio, which appears in the  $b^*$  value definition, and the short wavelength part of the SPD daylight.

The influence in the variations in the color coordinates with the yellow-blue content of the illumination appears to be corroborated when we make the same representation for the day with a high dust content (dst; Fig. 3). Measurements at sunrise on this day, due to the high dust content in the atmosphere, presented a larger relative quantity of power in the yellow-red wavelengths, in comparison to the rest of the days analyzed. Being the opposite trend to that of the other days, the directions of variation were contrary to those represented in Fig. 2. Again, the yellow-blue content of the illumination determined the variations of red-green type color, according to the value of the coordinate  $b^*$ , except for

the color stimuli with a high  $a^*$  value, for which there was also a major increase in the value of  $b^*$  at twilight.

Our first objective was not to analyze the object appearance changes under different daylight conditions. However, with further analysis of the results in the CIELAB space, it seemed reasonable to question whether the observed hue and chroma value changes can be understood as “real” changes in the color perceptual attributes. One approach comes from a modern color appearance model, especially the CIECAM97s, which allows us to evaluate them, instead of considering the CIELAB hue, lightness, and chroma.

In Figs. 4 and 5, we have replicated the conditions of Figs. 2 and 3, but the  $a_c, b_c$  diagram is deduced from the CIECAM97s simplified version model.<sup>15</sup> As in the CIELAB diagram, the chroma of an object is given by the Euclidean distance between the origin and the object ( $a_c, b_c$ ) coordinates. The hue is given by the angle formed by the segment that joins the origin and the point considered with the positive abscissa semi-axis. Clearly, the conclusions drawn when using the CIELAB diagram do not hold for the CIECAM97s diagram. For example, there is no evident change in the sense of the variation of the appearance from maximum solar elevation to twilight between the 2 days (cl1 and dst).

Also, many objects maintain approximately the hue from

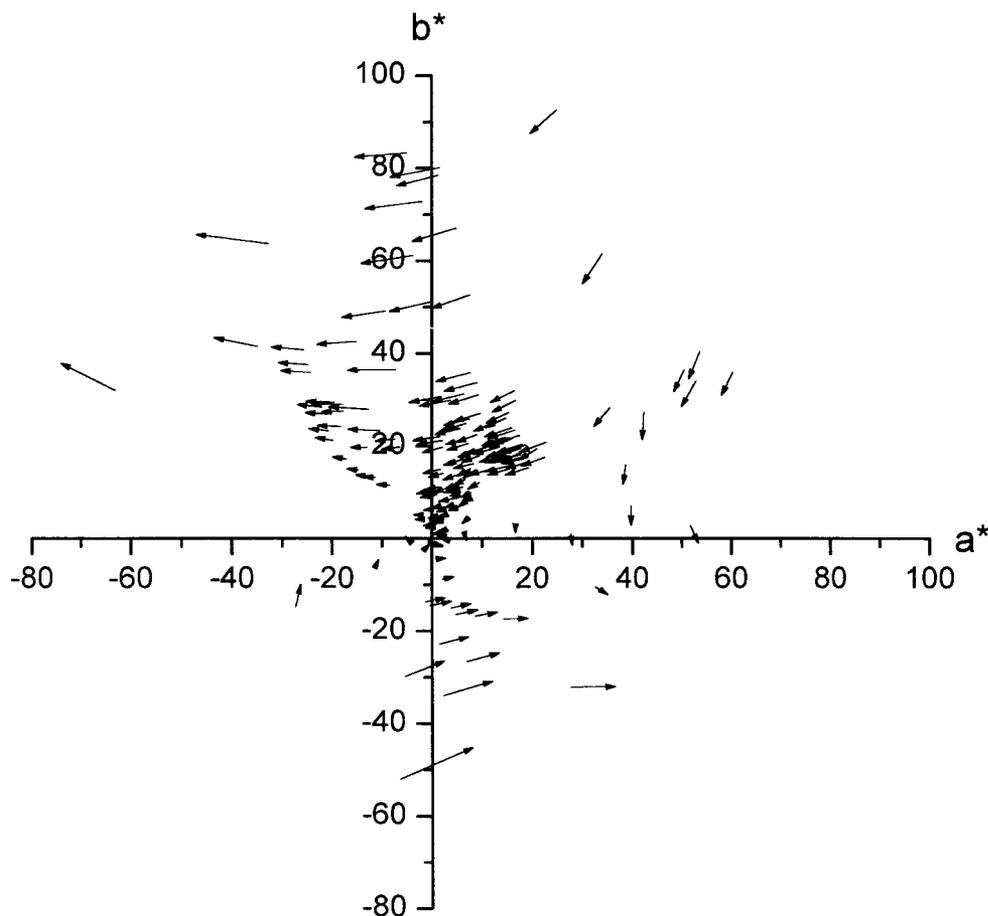


FIG. 2. CIELAB  $a^*$ - and  $b^*$ -chromaticity coordinates for the overall set of objects when illuminated by daylight corresponding to two solar elevations in a same day (clear day, c1). Each arrow joins the chromaticity coordinates obtained at maximum solar elevation and at twilight (marked by end of arrow).

midday to sunset or sunrise, with the most important change taking place in the chroma. But in general, changes in both attributes appear. In this representation, the magnitude of the changes are not so clearly related to the chroma of the object; some objects near the origin show similar changes to more saturated objects.

In calculating the values of  $J$  (lightness) and  $Q$  (brightness) given by the CIECAM97s model, both decrease when the illumination changes from maximum solar elevation to twilight, associated with the absolute value of the adapting luminance in each case,  $L_A$ .

### Color Differences

Our next step was to evaluate the color differences associated with the changes in daylight over the course of a day. Table III shows the mean CIELAB color differences and their standard deviation for 173 objects analyzed on each of the 7 days studied. Although the components of the color difference,  $\Delta a^*$ ,  $\Delta b^*$  and  $\Delta L^*$  are not independent variables, and the calculation of the standard deviation of the color differences can be questioned from a strictly statistical point of view, we did these calculations in order to evaluate the variability in the values we obtained.

In addition, to corroborate the slight variation in the  $L^*$  value, we made the same calculation for the differences of

only chromaticity. Both types of differences were calculated in three situations. First, we evaluated the color differences when the illumination corresponded on the one hand to the maximum solar elevation, and on the other to twilight. This led us to calculate the almost maximum color difference for an object over the course of the day considered. As shown in Table II, at times, the maximum solar elevation did not coincide exactly with the elevation at which the daylight chromaticity coordinates were farthest from those of twilight (solar elevation  $39.1^\circ$  in Table II), but the differences were minor, and we consider the maximum solar elevation to be a better reference.

Second, we calculated the color difference considering the maximum solar elevation and the elevation nearest  $5^\circ$ . This was done to calculate color differences during the day, when twilight is excluded. Finally, we calculated the color and chromaticity differences using daylight corresponding to the maximum solar elevation and that corresponding to the solar elevation closest to  $15^\circ$ , in order to study color variations only during the middle hours of the day.

As shown in Table III, the values calculated for the color differences in CIELAB units declined abruptly when we considered only the middle hours of the day, although this also occurred on some days when twilight was excluded. The tolerances that we should consider admissible in this work are difficult to specify because of the paucity of

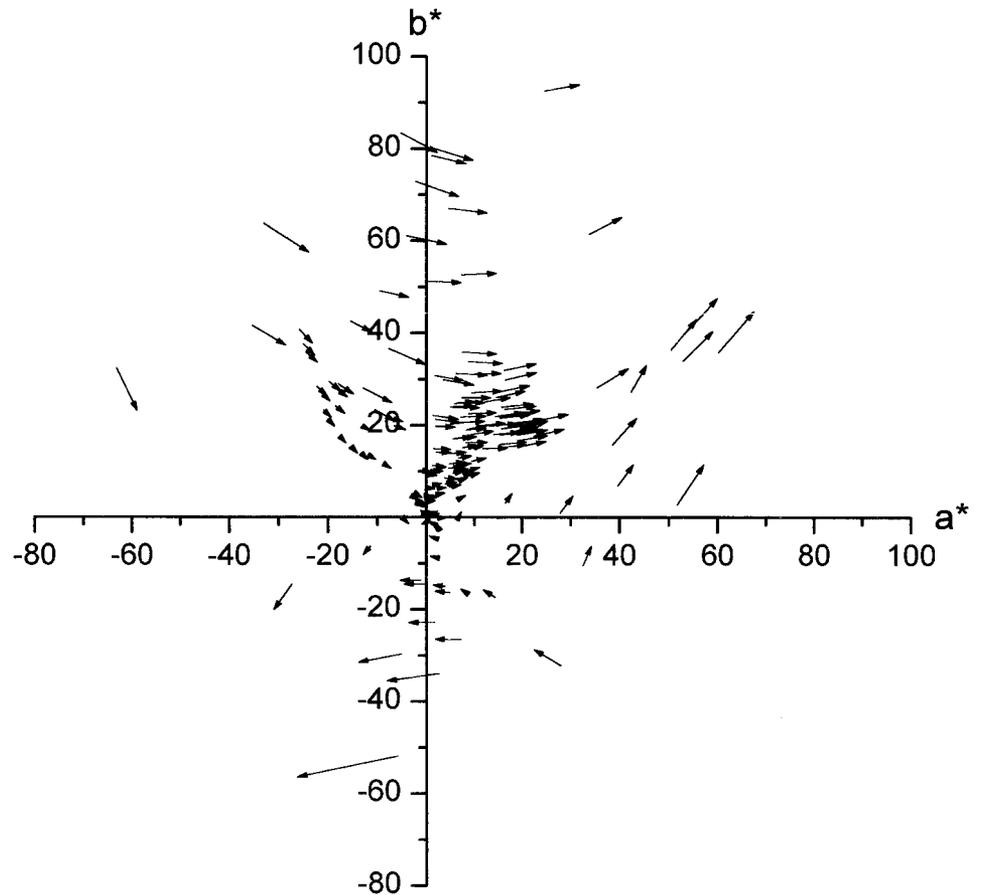


FIG. 3. CIELAB  $a^*$ - and  $b^*$ -chromaticity coordinates for the overall set of objects when illuminated by daylight corresponding to two solar elevations in a same day (dusty day, dst). Each arrow joins the chromaticity coordinates obtained at maximum solar elevation and at twilight (marked by end of arrow).

general recommendations in the literature, an understandable situation given that observational conditions decisively influence proposed color tolerances. Most of the recommendations on color differences refer to situations in which the colors of different objects are measured under the same illuminant, a situation opposite to the one we wish to analyze (the same object under different illuminants). Lozano<sup>16</sup> specified a *rigorous* color tolerance as being between 2 and 5 MacAdam units, and *normal* between 5 and 10 MacAdam units—that is, between 1.1 and 2.8 CIELAB units in the first case, and between 2.8 and 5.6 CIELAB units in the second, according to the usual conversion factors between color-difference units.<sup>17</sup> Vrhel *et al.*<sup>13</sup> adopted 3 CIELAB units, based on recommendations in the reproduction of objects, but 1 CIELAB unit is a usual color tolerance employed in industry.<sup>17</sup>

The color-tolerance concept is based on color discrimination. This we know to depend largely on observational conditions. In our case, we assume that to evaluate perceptual color differences, we should take into account that the color of the object viewed at different hours of the day or on different days compared in the viewer's memory, leading to greater color tolerances. Memory factors have been proven to lead to chromatic thresholds two or three times greater than those found by simultaneous comparisons.<sup>18</sup> On the other hand, just as temporal and spatial adaptation can also change, so can the appearance of the objects.

Based on these considerations, it appears too strict in our case to take one unit of CIELAB color difference as a tolerance, and thus, in agreement with Vrhel *et al.*,<sup>13</sup> we are inclined to adopt as a criterion for the evaluation of our results an acceptable color tolerance of 3 CIELAB units. If this is accepted, then the resulting color differences between the conditions of extremes in daily elevation normally fall outside the accepted limits. However, in the middle hours of the day, the differences are acceptable not only with this criterion but also if 1 CIELAB unit were adopted as the color tolerance.

In the case of considering on each day only the exclusion of twilight, we find that the color differences generally fall within the admitted tolerances, although, on some days, these are exceeded. Nevertheless, the high values of the standard deviation, indicative of a certain variability in the differences found, do not allow us to generalize this result.

Table IV presents the values for the color differences calculated at the limits of the different quartiles for the three conditions studied. As can be seen in the first of the conditions (extreme), we find color differences lower than 3 CIELAB units in the first quartile, but not for the rest of the quartiles. This corroborates the analytic results reflected in Table III. Similarly, for the middle condition, the limit color differences in each quartile are lower than the admitted tolerances, making it possible to generalize the conclusion drawn concerning the lack of variability of object color

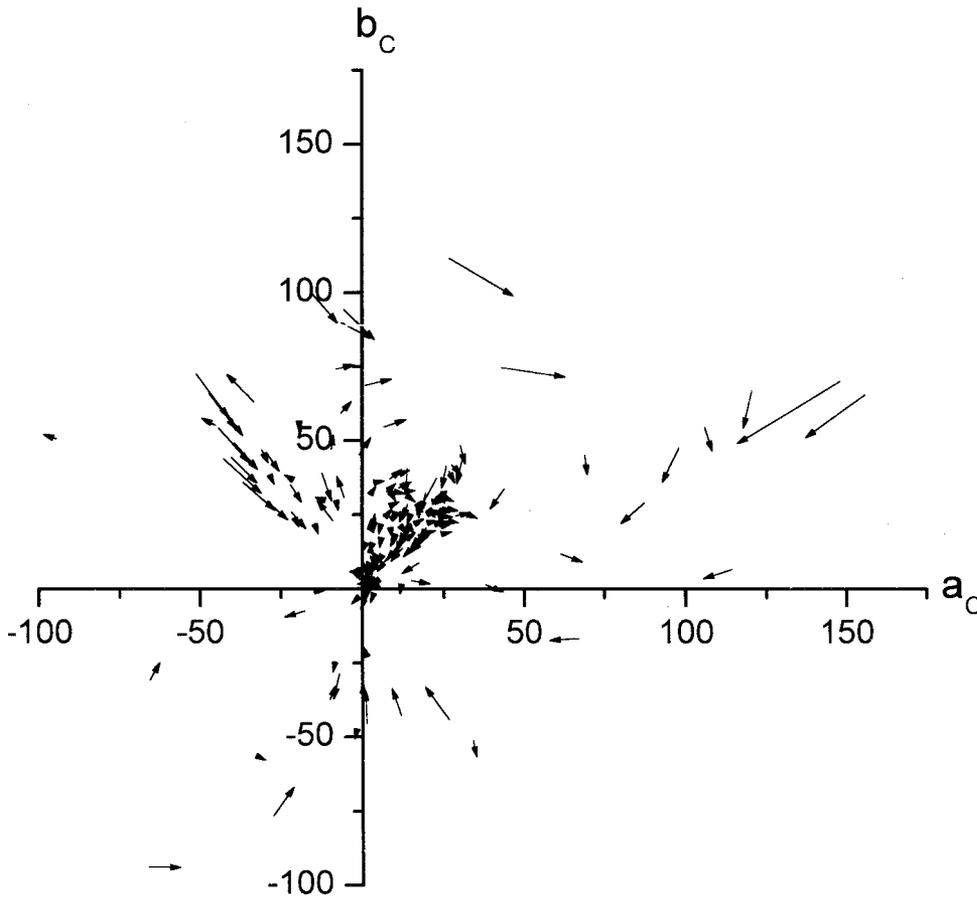


FIG. 4. CIECAM97s  $a_c$ - and  $b_c$ -chromaticity coordinates for the overall set of objects when illuminated by daylight corresponding to two solar elevations in a same day (clear day, c1). Each arrow joins the chromaticity coordinates obtained at maximum solar elevation and at twilight (marked by end of arrow). Calculations were done with reference to average surround.

when observed under natural illumination in the middle hours of the day. With regard to the intermediate condition (excl-tw)—that is, taking the natural illumination with the exclusion of twilight—almost 50% of the objects admit a tolerable color difference on any day, and on most days, even those are included in the third quartile. This indicates that the color variation in the color of objects is mainly, although not entirely, nonsignificant over the day, if we exclude twilight.

Table III indicates that when only the differences in chromaticity were evaluated, the values were very close to those found on calculating the complete color differences. These give us the idea that, as pointed out earlier, the differences in  $L^*$  are slight, a result common to all of the days.

Table V shows the differences in the means of hue and chroma, and the corresponding standard deviations. The values show the trends evident in Table III. The values for the differences in hue appear to be greater in relative terms than those of chroma, although all present high standard deviations, indicating a high variability in the individual values. In any case, Tables III and V show that the variations of the color differences, of chroma and of hue, were not significant when the color of objects was measured in the middle hours of the day—that is, when the sun is situated above a  $15^\circ$  elevation. During a year, the maximum solar elevation reached in Granada is  $76^\circ$  in the summer solstice and  $30^\circ$  in the winter solstice.

In addition, we compared the chromaticity coordinates of the same object on different days. Our aim was to study whether the atmospheric conditions could influence the CIELAB values calculated. Figure 6(a–d) gives an example of the results for 4 objects in different zones of the chromaticity diagram on 3 representative days under our atmospheric conditions: c11, ov1, and dst. The behavior for the rest of the days and objects was similar to that presented. At the maximum solar elevation, the chromaticity coordinates of the objects remained very similar, almost coinciding for the different days. When we added this to the results of the previous analyses indicating the scant variation in the middle hours of the day, we found no significant differences in the color of objects in the middle hours of the day, despite the fact that the measurements were made under very different atmospheric conditions. This finding is a consequence of the previously found similarity in the spectral distributions of daylight.<sup>14</sup> This does not mean that when the chromaticity coordinates are compared from an object under natural illumination in different locations the same degree of similarity will result. To test this, we need to have daylight measurements in other locations and settings. Nevertheless, the daylight measurements of other authors<sup>19–21</sup> present chromaticity coordinates, or correlated color temperatures, very close to ours for the middle hours of the day, indicating that the variability in the color coordinates of an object must not be very pronounced, although geographic

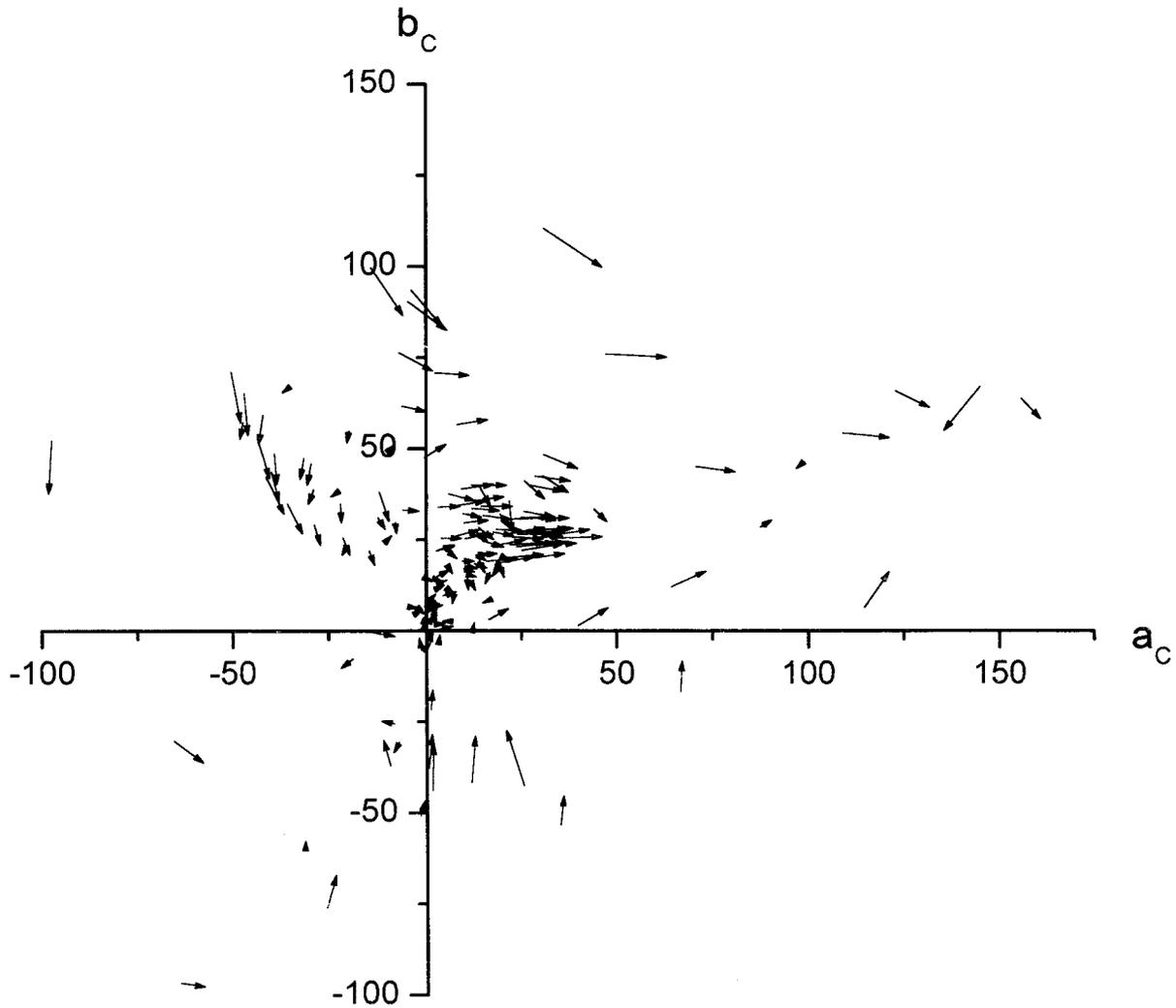


FIG. 5. CIECAM97s  $a_c$ - and  $b_c$ -chromaticity coordinates for the overall set of objects when illuminated by daylight corresponding to two solar elevations in a same day (dusty day, dst). Each arrow joins the chromaticity coordinates obtained at maximum solar elevation and at twilight (marked by end of arrow). Calculations were done with reference to average surround.

location may change. This idea should be tested experimentally. However, the differences between twilight must be considerable, because, at this time, the differences in daylight are greater in the set of measurements.<sup>14,19-21</sup>

In Fig. 6, we find that when the solar elevation lowers, the chromaticity coordinates follow different paths on the different days, especially for the day of high dust content, as might be expected. Nevertheless, the differences between

TABLE III. Average and standard deviation (in brackets) color and chromaticity differences in the CIELAB color representation system for the 173 objects and the different days.

Day	Color differences			Chromaticity differences		
	Extreme	Exc-tw	Middle	Extreme	Exc-tw	Middle
cl1	3.05 (1.93)	0.79 (0.60)	0.47 (0.36)	2.91 (1.86)	0.74 (0.57)	0.44 (0.35)
cl2	2.81 (1.80)	2.59 (1.59)	0.58 (0.41)	2.69 (1.74)	2.50 (1.54)	0.54 (0.39)
cl3	2.49 (1.62)	1.63 (1.07)	0.36 (0.27)	2.37 (1.56)	1.56 (1.03)	0.35 (0.27)
ov1	4.57 (2.80)	0.67 (0.52)	0.22 (0.16)	4.43 (2.74)	0.63 (0.50)	0.21 (0.16)
ov2	5.34 (3.28)	3.36 (2.02)	0.47 (0.31)	5.19 (3.21)	3.29 (1.99)	0.45 (0.31)
Mix	2.66 (1.70)	0.71 (0.54)	0.37 (0.28)	2.55 (1.64)	0.66 (0.52)	0.35 (0.27)
dst	4.62 (2.94)	2.03 (1.27)	0.86 (0.54)	4.53 (2.86)	2.02 (1.26)	0.86 (0.54)

Abbreviations (extreme, exc-tw, middle) mean differences between the color coordinates of the objects under maximum solar elevation and those when illumination is at twilight (extreme solar elevations), close to 5° (excluding twilight) and close to 15° (middle hours of the day), respectively.

TABLE IV. Color-difference limits in the three conditions of calculations for the different days.

	cl1	cl2	cl3	ov1	ov2	Mix	dst	
Extreme	1.60	1.48	1.23	2.39	2.69	1.40	2.26	1 <sup>st</sup> quartile
	3.04	2.78	2.36	4.63	5.14	2.65	4.35	Median
	3.93	3.58	2.80	5.66	6.50	3.46	6.39	3 <sup>rd</sup> quartile
Excl-tw	0.37	1.36	0.81	0.31	1.66	0.34	0.98	1 <sup>st</sup> quartile
	0.64	2.63	1.53	0.50	3.20	0.56	1.93	Median
	1.06	3.26	1.87	0.98	4.16	0.98	2.90	3 <sup>rd</sup> quartile
Middle	0.22	0.28	0.17	0.11	0.23	0.18	0.42	1 <sup>st</sup> quartile
	0.36	0.53	0.30	0.20	0.43	0.34	0.82	Median
	0.67	0.71	0.49	0.26	0.54	0.47	1.22	3 <sup>rd</sup> quartile

Abbreviations of days and conditions are the same as in Table III.

clear and cloudy days were not so notable, although they were sufficient to give color differences above the tolerances when comparisons were made of the color of objects illuminated in the different twilights.

### CONCLUSIONS

We have examined the color of natural and artificial objects under natural light. To do so, we calculated the color coordinates in the CIELAB system for a set of 173 objects for which the reflectances were known from the SPD of daylight measured at different solar elevations on 7 separate days. These days belonged to different seasons of the year and varying atmospheric conditions, from clear to completely cloudy days.

When we analyzed the color of the objects over a day, we found that the coordinates of each object changed notably from sunrise to midday. Toward evening, the values became similar to those of early sunrise. Our evaluations of the color differences revealed values that exceeded 3 CIELAB units, when the color of the objects under the maximum solar elevation was compared with that at twilight. These color variations were due primarily to the differences in the values of the chromaticity coordinates ( $a^*$ ,  $b^*$ ), because the  $L^*$  value hardly changed. In addition, we found that the greatest color differences were found for the objects having the highest chroma. These differences were present also in the hue, as well as the chroma, though the chroma main-

tained roughly the same value over the entire day, when the object presented chromaticity coordinates close to the axes of the CIELAB diagram. In general, the variations in the SPD of daylight over a day, which were of the yellow-blue type, caused variations of the red-green type when we analyzed the color of the objects in the CIELAB diagram. When the appearance is evaluated through the CIECAM97s model, changes in lightness and chroma are presented from midday to sunset, whereas the hue is maintained for many objects.

When we compared the color coordinates over an entire day, excluding only the solar elevations near twilight (lower than 5°), many of the objects presented color differences below tolerances. Furthermore, the average color differences during the middle hours (solar elevations above 15°), were consistently less than 1 CIELAB unit. These results were found for all the days considered. Therefore, except for drastic changes in weather, the color coordinates of an object remained, without significant changes over most of the day.

Also, the chromaticity coordinates of the objects changed little in comparisons of values for the central hours of different days; that is, whether the sky was cloudy or clear did not decisively influence the color coordinates of an object when measured at the maximum solar elevation in the same place. This result can have significant importance in tasks of detection, recognition, analysis, and synthesis of color under natural light, in addition to those of color

TABLE V. Average and standard deviation (in brackets) hue and chroma differences in the CIELAB color representation system for the 173 objects and the different days.

Day	Hue differences (°)			Chroma differences		
	Extreme	exc-tw	Middle	Extreme	exc-tw	Middle
cl1	4.73 (2.76)	1.14 (0.72)	0.70 (0.44)	1.79 (1.33)	0.47 (0.41)	0.28 (0.25)
cl2	4.46 (2.59)	4.35 (2.18)	0.76 (0.50)	1.64 (1.23)	1.49 (1.41)	0.36 (0.28)
cl3	3.37 (2.38)	2.53 (1.56)	0.67 (0.36)	1.46 (1.11)	0.95 (0.73)	0.16 (0.19)
ov1	8.35 (3.84)	1.01 (0.70)	0.40 (0.19)	2.47 (1.92)	0.40 (0.36)	0.10 (0.13)
ov2	9.96 (4.48)	6.49 (2.85)	0.78 (0.46)	2.84 (2.24)	1.74 (1.39)	0.29 (0.21)
Mix	4.16 (2.82)	1.05 (0.63)	0.64 (0.32)	1.56 (1.17)	0.42 (0.38)	0.18 (0.20)
dst	7.77 (4.17)	3.87 (2.04)	1.72 (0.88)	2.76 (2.24)	1.07 (0.94)	0.43 (0.39)

Abbreviations (extreme, exc-tw, middle) mean differences between the color coordinates of the objects under maximum solar elevation and those when illumination is at twilight (extreme solar elevations), close to 5° (excluding twilight) and close to 15° (middle hours of the day), respectively.

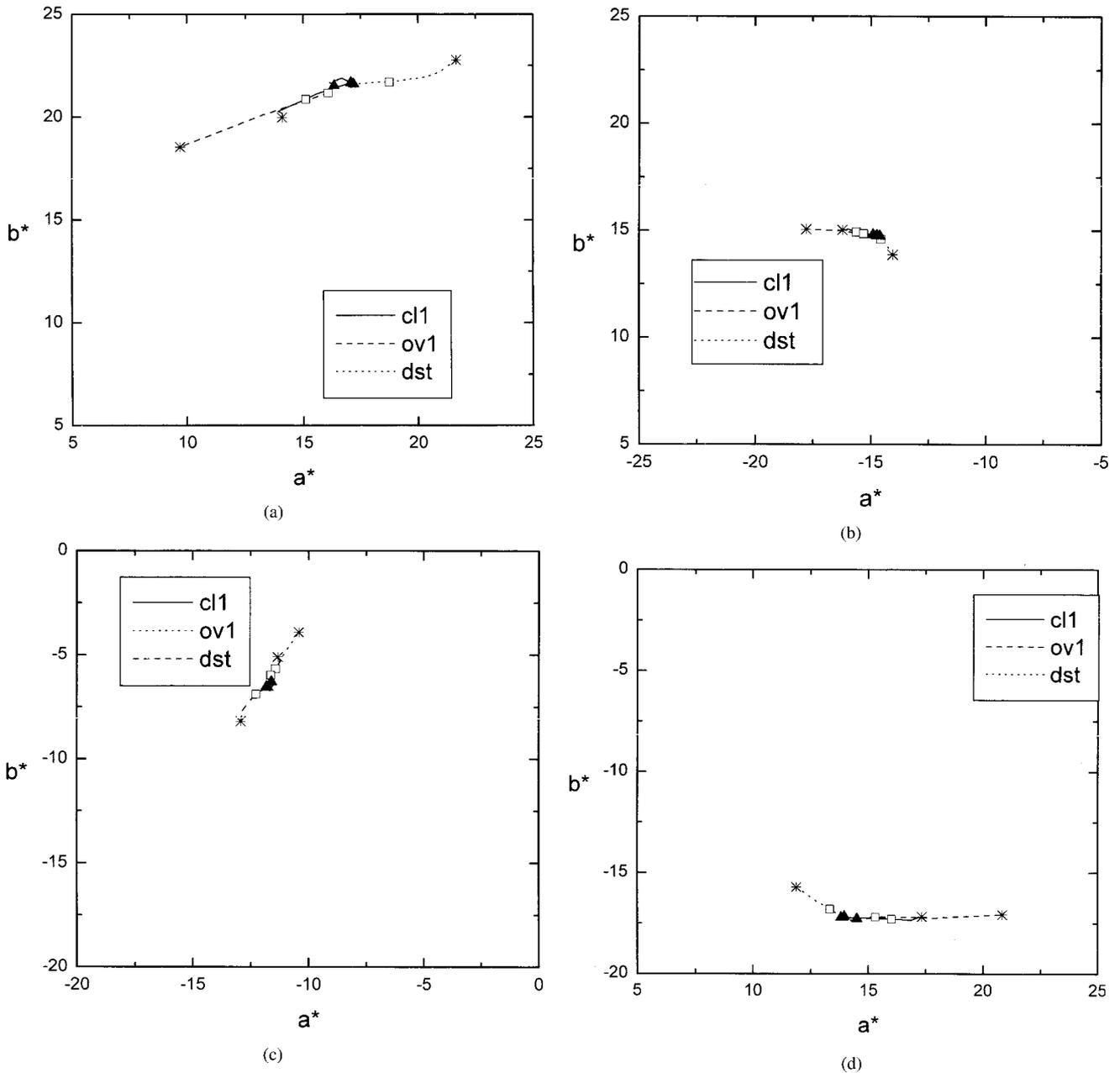


FIG. 6. Chromaticity trends in three different days (cl1, ov1, and dst) for four objects, (a) to (d). Each trend starts at maximum solar elevation and ends at twilight (marked with asterisk). The measurements with solar elevation near 5° and near 15° are also marked with open squares and filled triangles, respectively.

reproduction. Consequently, it would be useful to expand this study with a comparison of the color coordinates measured for the same object in the middle hours of the day at different geographical locations. In this way, we would achieve a more general characterization of the colorimetric variations of object color under natural light and in different settings.

We do not attempt to interpret these changes as variations in the appearance of the color of objects, but from this, we do deduce that it would be useful to conduct psychophysical experiments to evaluate the real changes in appearance of the color of objects seen under different phases of daylight.

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