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Reflectance and Energetic Imbalance: Colourimetric Evaluation of the NCS Colour Atlas

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The NCS atlas was evaluated in two ways. The first provided a series of exhaustive colourimetric measurements (reproduced in the electronic appendix available in http://www.uv.es/psicologica that were used for: (1) relating them to the descriptive parameters used by the atlas; and (2) analysing the general colourimetric properties of surface colours. The second type of evaluation examined the possibility of using the NCS atlas colourimetrically to specify colour tiles not belonging to it. The analysis of the relationship of the NCS with the colourimetric parameters showed that every NCS hue was associated with a specific chromatic angle and with one dominant wavelength. The relationships between NCS whiteness and CIE lightness, on the one hand, and between CIE and NCS chroma parameters, on the other, were high but not so closed. When the atlas was considered globally, it was observed that lightness strongly determined both the stimuli chromatic angle and CIE saturation. More specifically, for low lightness, the highest CIE saturations were observed for the chromatic angles associated with either of the spectrum extremes or with the purple line. For high lightness, on the contrary, the highest CIE saturation levels were observed for the chromatic angles related to the middle portion of the spectrum. The second type of NCS evaluation considered its possible utility for inferring the colourimetric parameters of samples not included in the atlas. A relatively low error level ($\Delta E < 8$) was detected, so it was concluded that the NCS atlas can be used for those practical applications that require colourimetric computations with medium or low levels of precision.

Both colour atlas and colourimeters provide colour measurements accepted by the scientific community (Kayser & Boynton, 1996, chap. 11 & appendix; Lillo, 2000; chap. 4; Mollon, 1999). Colourimeters give highly accurate results (highest reliability and precision) and are especially useful to work with colour additive mixtures. However, the information of measurement results is provided in terms of non-intuitive parameters and, more important, their high cost means that only laboratories with sophisticated instrumentation have access to them. In contrast, colour atlases provide a cheap and intuitive way to measure colours, although some degree of measurement imprecision is unavoidable. Such imprecision derives from the fact that the number of atlas

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colour tiles (several hundred) is clearly less than the amount of colours differentiable by the human eye (several million, see McCamy, 1998; Pointer & Attridge, 1998).

Several publications show colourimetric measurement results for the tiles contained in most common colour atlases. For Munsell, consult Travis (1991, appendix 1); for OSA, consult MacAdam (1978), Wyszechi and Stiles (1982, pp. 866-877); for DIN, consult Wyszechi and Stiles (1982, pp. 863-865). Using these publications, it is easy to determine equivalencies between tiles belonging to different atlases. We hope this paper will play a similar role for the NCS atlas.

The last version of the atlas created by the Scandinavian Colour Institute (SCI, 1997) to exemplify the Natural Colour System (NCS) has not yet been evaluated colourimetrically, probably because of its relatively recent publication. The first aim of our research, therefore, was to evaluate the NCS colour atlas and to present the results

Our second aim was to carry out a global colourimetric evaluation of the stimuli, such as NCS tiles, that produce colours by selectively reflecting light and that, due to this, are called "surface colours." Considering their number and variety, the 1795[1] NCS tiles can be considered an excellent sample of surface colours. The following parameters will be used to perform the colourimetric evaluation: dominant wavelength (λ_D), purity (p), reflectance (R), CIEu'v' saturation, and CIEu'v' chroma. The first experiments we will describe is related to both of the first two goals.

Our third goal was to determinate the precision level afforded by the NCS to measure surface colours. For this purpose, a second experiment was designed. In essence, it consisted of the use of the NCS atlas to obtain a colourimetric specification of 22 tiles selected from the Color Aid, a colour-sample set used very frequently by colour researchers (see, for example, Davies & Corbett, 1997).

The three above-mentioned specific aims can be considered part of a general goal: to allow researchers to reference colours using the NCS atlas as a tool when no colourimeter is available. To achieve this requires the description of the system used by the atlas to identify its tiles and also, obviously, of the parameters that will be used in the colourimetric evaluation.

NCS parameters

The acronym NCS corresponds to the initials of the English expression "Natural Colour System" (Hård, Sivik, & Tonnquist, 1996a, 1996b). This system is based on Ewald Hering's (1878) ideas, more specifically, on his opponent-processes theory (Kayser & Boynton, 1996, chap. 7). According to this theory, any visual stimuli can be described in terms of its similarity to the

[1] The NCS atlas contains 1750 different colour specifications. The number of 1795 results because most low saturation specifications (Chroma equal to 02 or 05) are presented two times (two colour samples).

six basic sensations: black, white, red, yellow, green, and blue. The two first sensations are achromatic, and the rest of them, chromatic.

The nomenclature used in the Scandinavian Institute atlas assumes that any visual stimulus can be partly described by three parameters, the values of which must add up to 100. The first parameter indicates tile similarity with perfect black (blackness level). The second one indicates similarity with perfect white (whiteness level). The third parameter indicates the stimulus chromatism (chroma). The second parameter value is usually not provided because, if the others are known, it can be deduced using the following equation:

$$\text{Whiteness} = 100 - (\text{blackness} + \text{chroma}) \qquad (1)$$

The Natural Colour System (NCS) assumes that any hue can be described in terms of its similarity to the four basic chromatic sensations (red, green, blue, and yellow), and postulates the existence of four hue scales: the Y-R scale (from yellow to red), the R-B scale (from red to blue), the B-G scale (from blue to green), and the G-Y scale (from green to yellow). One, and only one, of these scales must be used, in combination with a number ranging from zero to one hundred, to specify the hue of a specific stimulus. The lower the number, the higher the similarity between the hue of the colour and the one indicated by the capital letter to the left of the denomination (for example, B10G, corresponds to a slightly greenish blue), whereas high values mean the opposite (for example, B90G corresponds to a slightly bluish green).

The electronic appendix available in http://www.uv.es/psicologica shows that, in the Scandinavian Institute atlas, two kinds of samples are used. The first one includes all the chromatic tiles. The following is an example of the way they are named: "R80B 3040". The first four symbols (R80B) indicate that the sample hue is considered to be between pure red (R for "red") and pure blue (B for "blue"), although more similar to the latter (80). The other numbers of the colour denomination indicate, respectively, its blackness level (30) and its chromaticity (40), and one may deduce that the level of whiteness is 30 (100 – 30 – 40 = 30).

The denomination "N 5000" is an example of the way in which the atlas specifies achromatic tiles. "N" is used to indicate the achromatic character of the tile. This is confirmed by the two zeros at the right of the name (chroma level = 00). The first two digits inform about the blackness (50) and, taking into account the implicit whiteness (100-50 = 50), one may infer that "N 5000" is a medium grey.

Colourimetric parameters

For almost the last one hundred years, the CIE (Commission Internationale de L'Eclairage) has been developing a set of parameters for objectively specifying the characteristics of visible stimuli. These parameters can be quantitative (Lillo, 2000, chap. 2) or qualitative (Ibidem, chap. 4).

Reflectance is the proportion of light reflected by a surface and, consequently, the most important quantitative parameter to be specified in relation to the tiles contained in the NCS atlas. On the other hand, four parameters must be considered to specify their qualitative aspects: purity (P), dominant wavelength (λ_D), CIE saturation (Su'v'), and CIE chroma (C*). Each are briefly described below.

All visible stimuli have a metameric colour (physically different, perceptually identical) produced by the mixture of an equienergetic stimulation (or another reference white) plus a monochromatic stimulus. The wavelength (λ) of the latter indicates the dominant wavelength (λ_D) of the target stimulus. On the other hand, the relative proportion of monochromatic stimulation needed to metamerise a visible stimuli specifies its purity (P) on a scale ranging between 100 (only monochromatic stimulation is required to metamerise the target) and 0 (only equienergetic stimulation is needed).

Among experimental psychologists, saturation is a term frequently used to denominate the relative strength with which a specific hue is experienced (Kayser & Boynton, 1996; Lillo, 1999; Shepard, 1992). In order to differentiate this concept from what the CIE refers to as "saturation" (Hunt, 1987), the expressions *perceived saturation* and *CIE saturation* will be used.

Purity is just one of the factors that determines the level of perceived saturation. In general terms, the purer a stimulus is, the more saturated it is perceived. However, perceived saturation also depends on dominant wavelength (λ_D). In general, dominant wavelengths from both spectrum extremes produce more perceived saturation that those corresponding to the spectrum centre (Kulp & Fuld, 1995). To represent conjointly the effects of purity and dominant wavelength, the CIE proposes the computation of what is called *CIE saturation*. This is the distance, in the CIEu'v' diagram and multiplied by a constant (13), between the positions corresponding to the target stimuli and the equienergetic one.

If all the stimuli to be considered were similar in reflectance (or lightness) *perceived* and *CIE* saturation would be the same thing. However, common surfaces present important differences in their reflectances and, given a constant level of CIE saturation, the lighter the stimuli, the higher will be its perceived saturation. To take this fact into account, CIE proposed (see CIE, 1978; or Lillo, 2000; chap. 4) the following equation:

$$C^* = Su'v' \bullet L^*, \qquad (2)$$

where C* represents what we have called *perceived* saturation and CIE refers to as "chroma," Su 'v' represents CIE saturation, and L* is the lightness computed from the level of relative reflectance.

EXPERIMENT 1. NCS COLOURIMETRIC EVALUATION

As mentioned previously, first experiment had the following two goals:

1. To perform an exhaustive colourimetric measurement of the NCS atlas 1795-tile set.

2. From the results of such an evaluation, to deduce the kind of properties that can differentiate surface colours from other chromatic stimuli.

Considering in the first place the quantitative aspects of colourimetric evaluation, it is important to point out that we did not expect an optimal correlation between CIE lightness (L) and NCS whiteness (W). Although the colloquial meaning of the latter is almost synonymous with lightness, this is not applicable to CIE whiteness because, as is explicitly indicated by the equation (1), this parameter value depends on blackness (B) and on NCS chroma (they must add up to 100). That is why light stimuli do not always have high NCS whiteness values: The more NCS chroma they have, the lower the possibility of obtaining high whiteness values. To compensate this fact, we propose applying the following equation:

$$W' = \frac{W}{100 - C} \bullet 100 \qquad (3)$$

Where "W'" represents "corrected whiteness," "W" is the standard NCS whiteness, and "C" is the NCS chroma.

We now consider the predictions related to the interaction between the quantitative and the qualitative stimuli properties. Our hypothesis is that, for surface colours, there will be a close relation between both types of properties. Let us examine the reasons for this prediction.

To be perceived as chromatic, a surface must preferentially reflect a portion of the visible spectrum. If this portion includes what the CIE luminous efficiency function (see, for example, Pokorny & Smith, 1986, Table 8.6) refers to as "not very efficient" wavelengths to produce a quantitative visual effect, the expected result is a stimulus with low reflectance and high purity-saturation-chroma. If the portion includes quantitatively more efficient wavelengths, then reflectance will be higher. It does not seem possible to have stimuli that are simultaneously high in purity-saturation-chroma and in reflectance, because higher reflectance values only can appear when a large proportion of energy is reflected in all, or almost all, wavelengths.

METHOD

Apparatus and measurement procedure. A PR-650 Photoresearch spectrocolourimeter connected to a computer was used for the measurements (photometric, colourimetric, and radiometric). To obtain an illumination as flat as possible in its spectral distribution, fluorescent lights were avoided. Instead, we used incandescent lights of 3630 K (275.5 MR) and filters to transform this value into 5754 K (173.8 MR), this value is very similar[2] to the one recommended by the Atlas (illuminant C)

Each tile was consecutively placed in the middle of a booth illuminated with the aforementioned type of light that reached the tile after passing through a diffuser filter. Illuminance was adjusted at 200 luxes. A one-degree angle was used in the spectrocolourimeter to receive the light reflected by the tiles. The position of the spectrocolourimeter prevented mirror-type reflections.

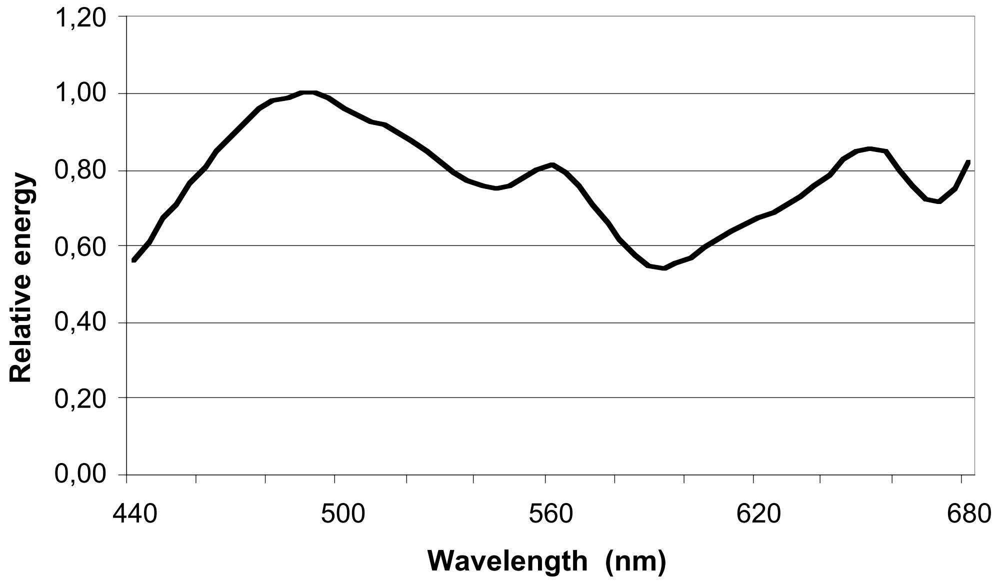

Figure 1. Illuminant espectral distribution.

Figure 1 shows the spectral distribution for the type of illumination used, in particular, its excellent quality. All the wavelengths reveal significant energy accumulation. There were no sharp variations in the levels of energy for the proximate wavelengths. The level of energy was similar at the different parts of the spectrum.

RESULTS

Each point in Figure 2 corresponds to an NCS atlas tile. The high accumulation of points near the illumination used (u'= 0.194; v'= 0.484) produces a black spot. It can be observed that the points do not cover the whole diagram. Instead, they are concentrated in the area delimited by an irregular line that from now on will be referred to as the *NCS colour area.*

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[2] In fact, we got a better approach than Hård, Sivick and Tonnquist (1996a; pg. 189). They used a colour temperature of, approximately, 5400 K. We measured 5754 K.

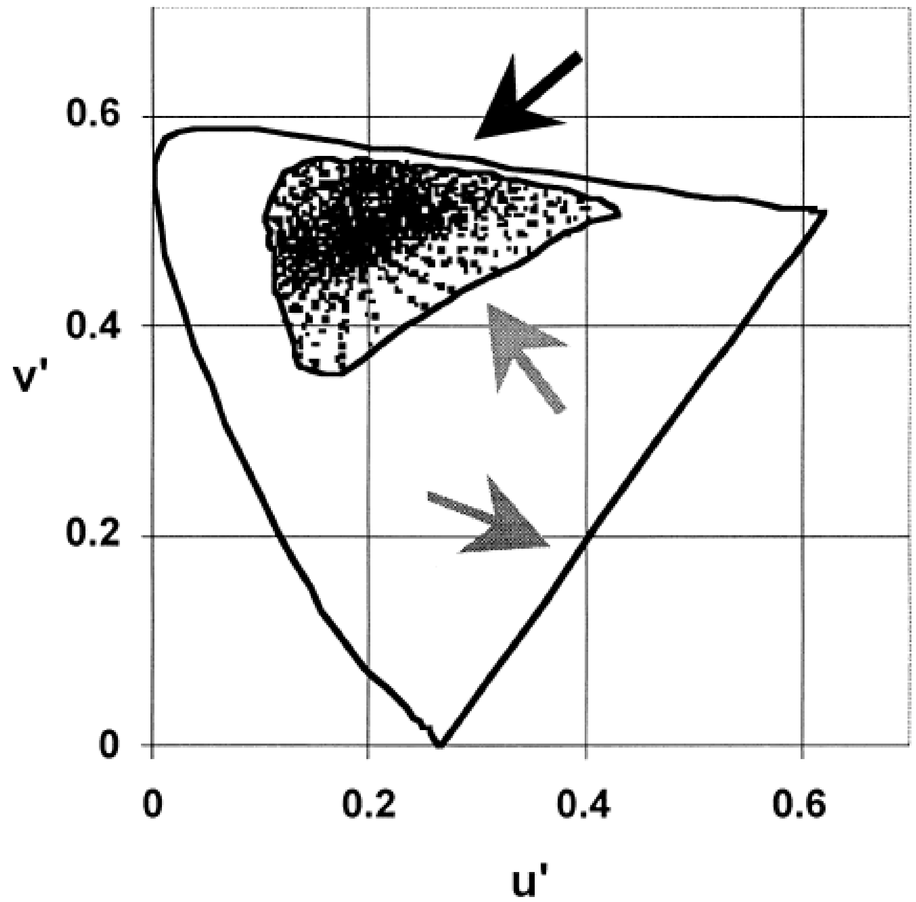

Figure 2. NCS tiles chromatic co-ordinates.

Two conclusions can be drawn, taking into account the position occupied by the NCS colour area in the chromaticity diagram. The first one is that not all the colours that can be created by a mixture of luminous stimuli have a metamer in the atlas stimuli (in that case, the points should cover the entire diagram). The second conclusion is that there are important differences in the maximum purity level corresponding to every dominant wavelength. Arrows are used in Figure 2 to facilitate comprehension of the second conclusion. That is, the black arrow showing the proximity of u’ = 0.23; v’ = 0.55 indicates that, for some dominant wavelengths, there is practically no space between the line that surrounds the NCS colour area and the diagram perimeter. Consequently, these dominant wavelengths have high purity levels. On the other hand, two grey lines are used to indicate that, for the dominant wavelengths related to the purple line (the one that goes from point u’ = 0.27; v’ = 0.00; to point u’ = 0.61; v’ = 0.51) and both spectrum extremes, there is a large space between the NCS colour area and the perimeter of the diagram.

Figure 3 shows the spectral distributions of: (a) sodium light; (b) the NCS tile with the highest purity (Y1080; u' = 0.235; v' = 0.553; the closest to the diagram perimeter); (c) the NCS tile with the highest CIEu'v' saturation (R1580, the farthest from the equienergetic point). Low-pressure sodium light is probably the best example of perfect purity that can be found among the common visual stimuli in daily life. This type of light is provided by the familiar orange-yellow bulb commonly used to light some streets and roads. As clearly seen in Figure 3.A, its high purity derives from the fact of that all the light it emits is concentrated within a very short range of wavelengths (between 580 and 600 nm). On the other hand, Figures 3.B and 3.C show that, even considering the purest and the most saturated NCS tiles, the reflected energy occupies a relatively broad wavelength range.

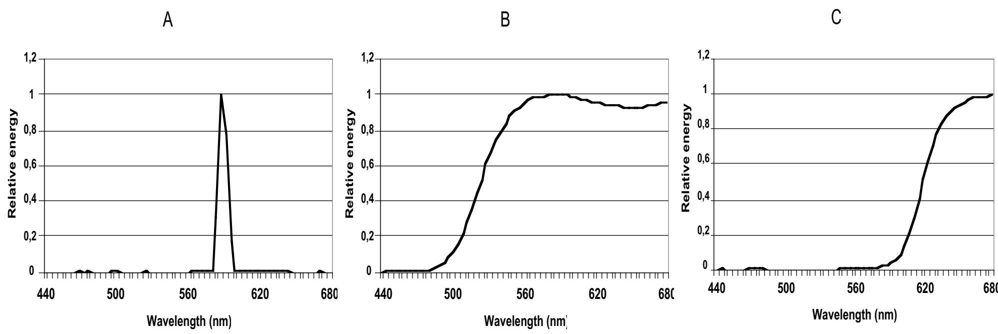

Figure 3. Spectral distributions of three stimuli.(A) Low pressure sodium light. (B) Y1080 tile (NCS atlas maximum purity). (C) R1580 (NCS atlas maximum CIEu'v' saturation).

Comparison of the different parts of Figure 4 shows what is probably the most significant result obtained in the NCS colourimetric evaluation: There was a strong relationship between the reflectance value and the positions occupied by the NCS in the diagram. For reflectances of less than 5% (Figure 4.A), there were points on, or near, the perimeter of the NCS colour area for the dominant wavelengths corresponding to the purple line or to the spectrum extremes. On the other hand, the same figure shows a "gap" between the perimeter of the NCS colour area and the black points corresponding to the stimuli. To facilitate the localisation of this gap, two greys arrows are included. They are also used in Figures 4.D and 4.F, indicating gaps in different positions of the NCS colour area.

The displacements in the NCS stimuli positions observed in Figure 4 can be described as follows. At lower reflectance levels (R < 5%; Figure 4.A), there is a gap for medium dominant wavelengths (near 570 nm). As reflectance increases (Figures 4.B to 4.D) to 30 %, the gap moves and affects dominant wavelengths related to the purple line and to spectrum extremes. When reflectance reaches 60% (Figures 4.E to 4.G), the gap increases its magnitude considerably and begins to spread over more parts of the NCS colour area. Due to this, most colours have dominant wavelengths near 570 nm (the ones that usually produce the best examples of yellow) or, with a very low level of CIEu'v' saturation, 480 nm. And when reflectance reaches very high levels (R > 60%), all the points are located close to the one corresponding to the illuminant and, consequently, have very low levels of CIEu'v' saturation.

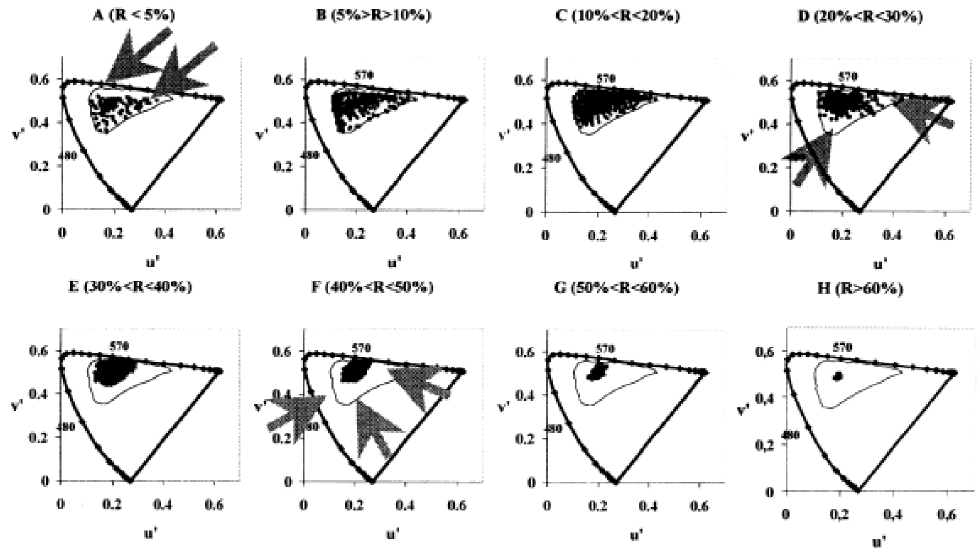

Figure 4. Reflectance and chromatic co-ordinates.

Figure 5 shows the strong relationship observed between NCS-hue parameter and dominant wavelength. Each part of Figure 5 shows the chromatic co-ordinates for the tiles corresponding to four NCS-hues. For example, the part identified as "Series 0" presents the points corresponding to denominations "Y" (yellow), "R" (red), "B" (blue), and "G" (green). Given the proximity and contiguity between the points belonging to each denomination, four straight lines between the equienergetic point and the perimeter of the NCS colour area are perceived. A similar effect is observed for the rest of the series shown in Figure 5: The graphic representation of stimuli with a specific graphic denomination produces a non-curved line. In Table 1 is specified the dominant wavelength (and the chromatic angle[3] corresponding to each NCS-hue).

3 Although for identification purposes dominant wavelength (λ_D) and chromatic angle (H*) can be used interchangeably, H* is more useful to specify the discriminability between pairs of stimuli.

Figure 5.

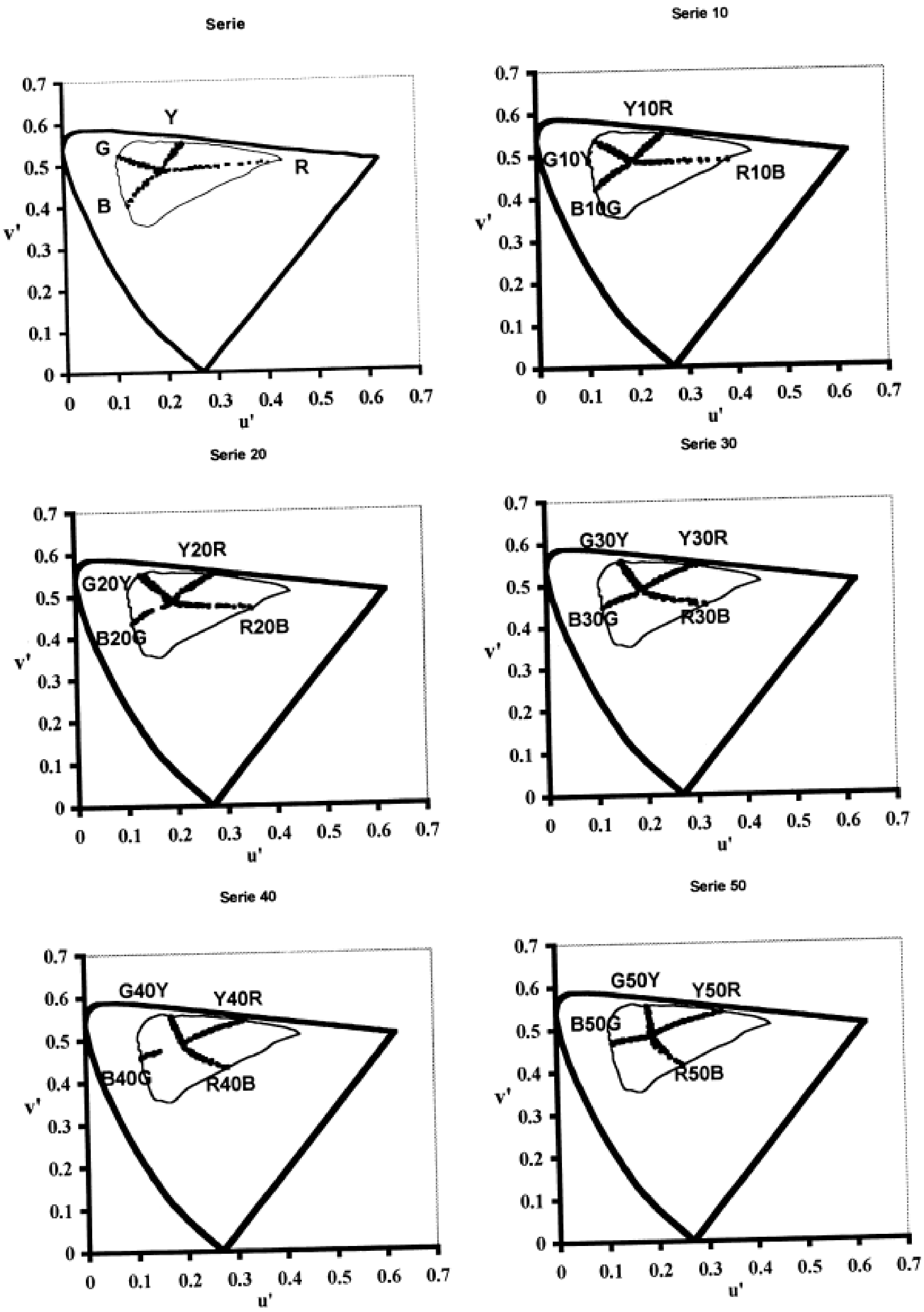
Serie
Y
G
R
B
Serie 10
Y10R
G10Y
R10B
B10G
Serie 20
Y20R
G20Y
B20G
R20B
Serie 30
G30Y
Y30R
B30G
R30B
Serie 40
G40Y
Y40R
B40G
R40B
Serie 50
G50Y
Y50R
B50G
R50B
v'
u'

Figure 5 (cont.).

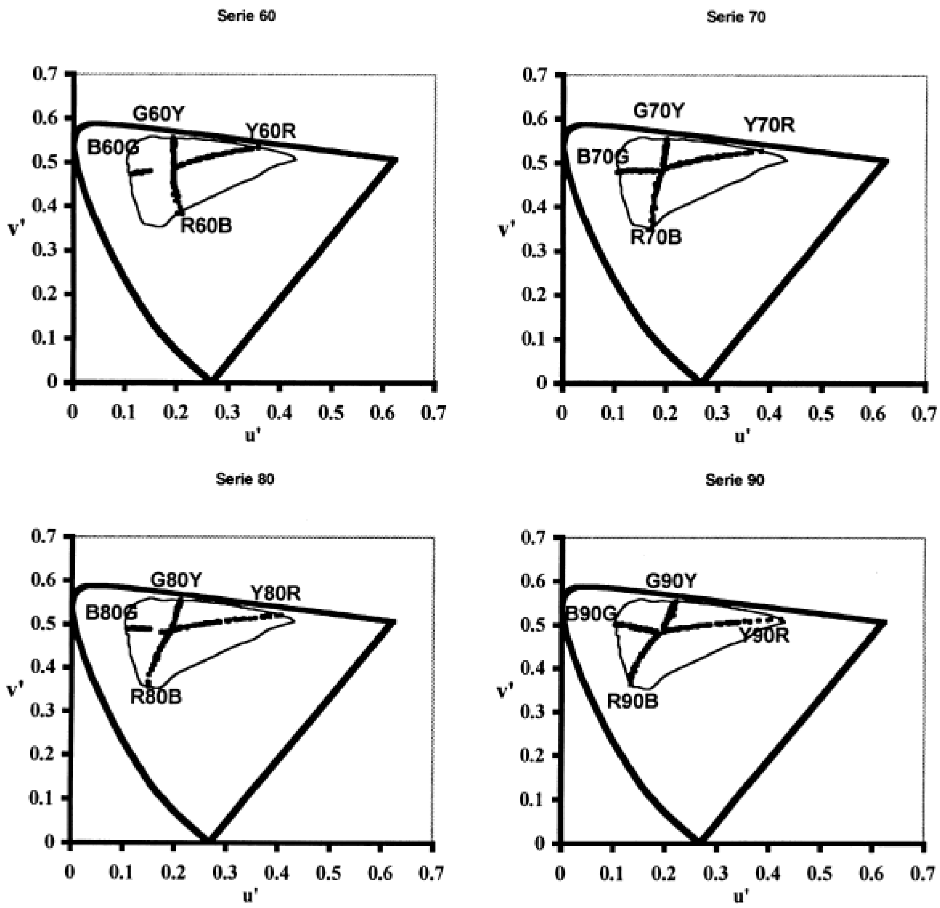

Table 1. Dominant wavelength (λ_D) and chromatic angle (H*u'v') for the 40 NCS hue denominations used in the atlas. To compute both parameters, the chromatic co-ordinates of most saturated of each denomination tile were used. White reference co-ordinates were u'= 0.194; v' =0.484. Following the common practice (see, for example, Wyszecki & Stiles, 1982, figure 1. 3. 4 ; Lillo, 2000, figure 4.6), negative wavelengths indicate complementary dominant wavelength values.

DEN. NCS	λ_D	Angle		Den. NCS	λ_D	Angle
Y	576.5	59.75		B	485.0	225.80
Y10R	580.0	48.67		B10G	486.0	219.52
Y20R	583.0	39.86		B20G	488.0	212.07
Y30R	588.0	29.85		B30G	489.9	205.40
Y40R	590.5	24.94		B40G	491.0	199.48
Y50R	593.5	21.02		B50G	493.5	190.88
Y60R	598.0	16.55		B60G	494.0	187.88
Y70R	602.5	13.01		B70G	495.5	183.36
Y80R	608.0	10.03		B80G	496.5	177.59
Y90R	614.0	08.07		B90G	502.5	166.76
R	629.0	05.29		G	512.0	155.52
R10B	-496.5	00.48		G10Y	530.0	144.70
R20B	-498.5	354.29		G20Y	544.0	135.62
R30B	-502.5	343.33		G30Y	557.0	119.40
R40B	-523.0	328.02		G40Y	563.0	106.88
R50B	-549.0	310.20		G50Y	566.5	96.94
R60B	400.0	279.49		G60Y	568.0	91.40
R70B	471.0	260.40		G70Y	570.0	84.85
R80B	477.5	249.41		G80Y	572.0	77.52
R90B	481.0	238.93		G90Y	574.0	69.25

Following the graphic description of NCS colourimetric evaluation, let us now consider the correlation values between some CIE and NCS parameters. With regard to the quantitative parameters, we point out that the lineal correlation between the NCS whiteness (W) and the CIE lightness (L*) was .86. The standard error between these two variables was 13.07. As expected, substituting "W" with "W' " (see Equation 3), the lineal correlation increased to .94 and the standard error decreased to 5.75. Regarding the qualitative parameters, the correlation between the NCS chroma and CIE C* (r = .93; standard error = 8.0) was higher than the one between NCS chroma and CIEu'v' saturation (r = .86; standard error = 10.78).

DISCUSSION

Each point of a colour space or of a chromaticity diagram theoretically corresponds to an infinite number of physical stimuli because, in the artificial world of research laboratories, the same colour experience can be elicited by very different physical stimuli. For example, there are unlimited ways to create white light by mixing two monochromatic stimuli but, no matter how different they may be, all of them are represented at the same point because they all produce the same sensation ("white").

However, this situation does not apply in natural environments because, in that case, several factors limit the number of possible colours and the number of physical stimuli that can produce a specific colour.

The characteristics of light reflected by surfaces depends on two factors: (1) the spectral distributions of the illuminant, and (2) the spectral distributions of the surfaces´ reflectance. Research carried out over the last forty years (Judd, MacAdam, & Wyszecki, 1964; Lennie & D'Zmura, 1988; Maloney, 1986; Maloney & Wandell, 1986; Shaw, Westland, & Thompson, 1999) has shown that, in natural environments, these two factors have limited ranges of variation and, consequently, the number of possible metamers is also limited.

The aforementioned works reveal that natural environments tend to reduce the number of stimuli that can be represented by a point in a chromaticity diagram. Our results show that the area occupied by a representative sample of common surfaces (the NCS colour area) is just one part of the diagram (Figure 2), which varies its extension and localization depending on reflectance (Figure 4). Why this latter restriction? Why are low reflectances associated with λ_D of both spectrum extremes, but high reflectances with λ_D near 570 nm? The explanation is based on differences in luminous efficacy of wavelengths: Given a specific purity level, higher reflectance corresponds to the more efficient wavelengths (the centre of the spectrum), and lower reflectance to the less efficient ones (the extremes and the purple line).

In Figure 5, the straight lines show that there is a strong relationship between what the NCS atlas refers to as hue and λ_D (or H*). Consequently, the atlas makes it very easy to select stimuli in terms of their λ_D. On the other hand, it makes it very difficult to agree that what is referred to as "hue" in the atlas really is what is commonly denominated as such. The causes of our scepticism will be explained in the following paragraphs.

Research focusing on the Abney effect (i.e., Kurtenbacket et al., 1984; McAdam, 1950) and the Bezold-Brüke effect (see, for example, Boynton & Gordon, 1965; Valverg et al., 1991; Pridmore, 1999a, b) show that stimuli with the same λ_D can be perceived with different hues when differing in saturation (the Abney effect) or in intensity (the Bezold-Brüke effect). More important, research carried out by Boynton and Olson (1987, 1990) in the late eighties at the University of California revealed a strong relationship between lightness (or reflectance) and basic categories. For example, the yellow category is only used in response to stimuli with high reflectance levels. Considering all this evidence, it does not seem accurate, for example, for the NCS atlas to use the denomination “yellow” (“Y”) both for light and dark stimuli. On the other hand, it seems very reasonable to infer that other denominations are more accurate for dark stimuli. A recent study (Lillo et al., in preparation) has provided results that support this.

The last aspect to consider is the relationship between NCS whiteness (W) and CIE lightness (L*). As expected, the transformed whiteness (W’) correlates higher with lightness. Even considering this improvement, W’ and L* are not totally equivalent. Taking this into account, if one wishes to compute the exact L* value that corresponds to a specific atlas tile, the information about its reflectance (Ref.) provided by the electronic appendix available in http://www.uv.es/psicologica may be used in combination with the following equation proposed by the CIE (1978):

$$L^* = 116\left(\frac{\mathrm{Ref}}{100}\right)^{1/3} - 16 \qquad (4)$$

For example, the electronic Appendix shows that the stimulus “Y0580” has a reflectance equal to 47.1 % and, consequently, an L* equal to 74.25. This value is almost the same (75) that equation (3) computes for W’ and, of course, very different from the whiteness (W) value implicit in the stimulus denomination (W = 15; it can be computed using equation 1).

Equation 3 does not quite provide values that are completely equivalent to L*. Why is there a small difference between L* and W’? One could speculate that the cause might lie in H-K effect (Ayama & Ikeda, 1998; Ikeda, Yaguchi, & Sagawa, 1982). More specifically, readers are reminded that in Equation 2, the calculation of L* only takes into account the stimulus achromatic level (its luminance). However, the H-K effect shows that chromatic parameters also influence the perceived lightness and, consequently, could influence the whiteness level (W) of the NCS tiles.

EXPERIMENT 2

The main goal of this experiment was to asses the validity of the NCS atlas as an instrument to infer colourimetric values for common colours. For this purpose, eight observers used, in a matching task, the atlas to locate the tiles that were most similar to a sample of surface colours from another standardised set (the Color Aid Set). Because the number of discriminable colours is always superior to the number of tiles that an atlas can contain, we expected to observe some differences between the real colourimetric parameters corresponding to the Color Aid tiles, and their estimation based on the use of NCS atlas. The larger such differences, the less useful would be the NCS to specify colour samples.

The CIE Lu'v' colour space includes the parameter ΔE* to specify perceptual differences appreciable between pairs of colour surfaces. Its value is computed using the following equation proposed by the CIE (1978):

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta H^{*2} + \Delta C^{*2}} \qquad (5)$$

To divide the perceptual difference (ΔE*) in terms of lightness (Δ L*), hue (ΔH*), and saturation ("chroma", Δ C*') presents several advantages. First, error magnitudes of these different aspects can be compared. Second, each parameter has a clear and homologated meaning. Third, it is relatively easy to understand the meaning of specific Δ E* values because this parameter has been used in other works (see Birch, 1993, p. 75) to measure the differences between stimuli used in standardised colour-discrimination tests and, in addition, can be used to measure the differences between the contiguous tiles of any homologated atlas.

METHOD

Subjects and apparatus. Eight observers participated in the matching task. They all were members (students or teachers) of the Complutense University of Madrid and were between 23 and 42 years old. A battery of chromatic tests was used to verify that no one had colour vision disturbances. The test battery consisted of the Ishihara test (1917, see, for example, Birch, 1993, or Fletcher & Voke, 1985; pp. 276-278), the City University Colour Vision Test (CUCVT; Fletcher, 1980), and the "Test para la Identificación de los Daltonismos" (TIDA [Test to Identify Colour-Blindness]; Lillo, 1996).

Table 2 shows a colourimetric description for the 22 Colour-Aid stimuli used in the matching task. Five parameters are presented: reflectance (R), chromatic co-ordinates (u', v'), lightness (L*), chromatic angle (H*), and chromaticity (C*). The first two were directly measured by the spectrocolourimeter. Last three were computed using the following equations:

$$L^* = 116 \left(\frac{\mathrm{Ref}}{100}\right)^{1/3} - 16 \qquad (6)$$

$$H^* = \arctan \frac{v^*}{u^*} \qquad (7)$$

$$C^* = \sqrt{u^{*2} + v^{*2}} \qquad (8)$$

Obviously, to apply equations (6) and (7), it was necessary to compute u* and v* previously in the conventional way (for more details, see Lillo, 2000, chap. 4).

Table 2. Colorimetric description of colour-aid samples.

Color Aid Denomination	R	u'	v'	L*	H*	C*
YO-T1	41.71	0.26	0.54	70.67	35.29	88.23
Ygw-T1	54.02	0.18	0.53	78.48	92.01	53.80
G-T1	21.13	0.12	0.50	53.10	165.86	45.99
C-Hue	13.61	0.13	0.41	43.68	232.11	53.17
Bw-Hue	56.62	0.16	0.34	79.97	260.09	145.11
V-T3	16.92	0.21	0.42	48.16	290.24	43.38
RC-T3	30.25	0.27	0.47	61.88	354.40	68.52
G-Ex	14.61	0.12	0.50	45.10	166.71	42.31
RG-Ex	11.09	0.39	0.48	39.73	0.89	105.95
R-LT	54.67	0.24	0.49	78.85	13.54	51.42
Gray-3	10.48	0.19	0.48	38.70	19.13	3.95
Gray-8.5	51.00	0.20	0.48	76.68	24.90	9.57
R-P2-3	40.63	0.22	0.49	69.92	16.45	27.26
RO-P3-3	35.87	0.22	0.50	66.42	31.02	29.65
YO-P2-1	30.47	0.24	0.53	62.06	44.66	57.33
Y-P3-1	21.11	0.22	0.53	53.08	55.77	40.02
Ygw-P4-1	11.71	0.21	0.52	40.76	60.10	24.57
G-P1-1	29.82	0.15	0.52	61.50	138.06	41.29
BG-P2-2	27.88	0.16	0.48	59.78	182.19	20.98
C-P3-2	22.04	0.17	0.47	54.07	217.69	12.59
V-P2-1	7.63	0.19	0.44	33.20	277.49	19.27
M-P2-1	11.82	0.25	0.47	40.93	348.55	36.76

Procedure. Each observer performed the task looking inside a cubic booth measuring 1 x 1 x 0.5 m located in the Work Psychology laboratory (for more details see Lillo, Vitini, Carbonell, & Martin, 2000). All the walls of the booth were painted a medium grey (L* = 50). After the appropriate adjustments, the booth lamps produced the type of light represented in Figure 1. The illuminance on the tiles was 200 luxes. There was no glare on the tiles.

Each subject looked at twenty-five tiles. The first three were used to familiarise subjects with the task (training phase). The tiles were randomly selected from the Color Aid full set, with the exception of the tiles included in Table 2. The remaining 22-tile set was presented randomly to all the observers (experimental phase). We will only comment upon the results related to this set.

At the beginning of the matching task training phase, observers were informed about the organisation of the NCS atlas, and about the most logical way to find the most similar tile to a target among the NCS tiles. Specifically, they were taught the following: (1) to use the plate containing the colour circumference to find the most similar hue to the target colour. (2) To perform an exhaustive search for this plate and the two next most similar plate hues, searching for the tile with the maximal similarity to the target colour. Each observer was informed that it was possible that no atlas tile would be completely similar to the target colour. In that case, the correct response was to indicate either the most similar tile or the two tiles between which the colour target could be placed.

RESULTS

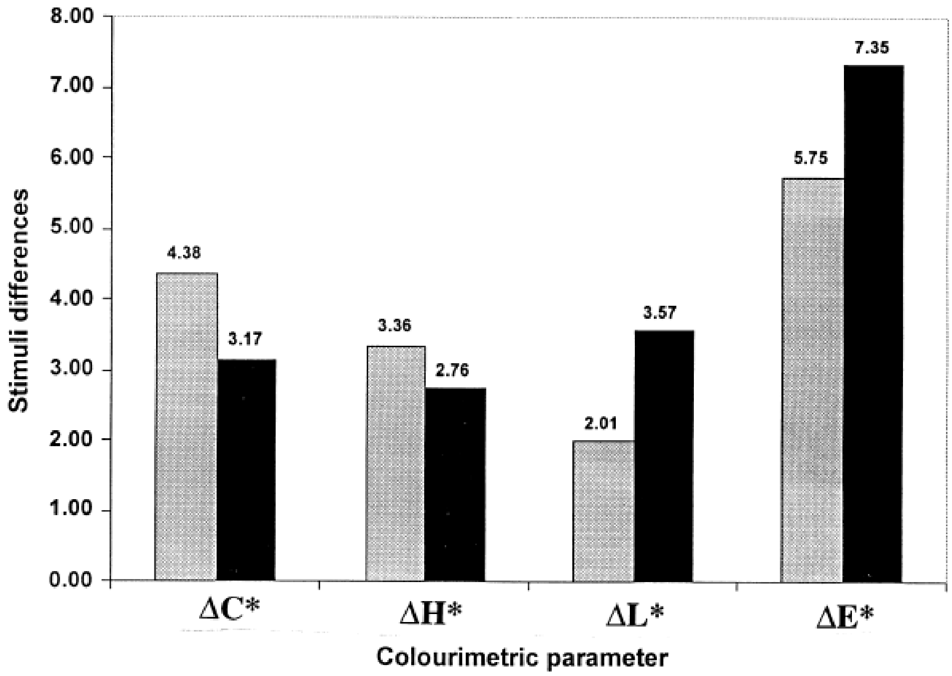

Figure 6. Inter-individual variation (light bars) and variation between real and inferred colourimetric values (dark bars).

In Figure 6, two types of bars are used to refer to two different aspects of the task performance. Light bars represent between-observer variability (mean of the standard deviations for each tile) and are therefore related to the following question: How much did the observers differ in their choices? On the other hand, dark bars represent the difference between (1) the Color Aid real colourimetric parameters and (2) the parameters inferred from the mean of the NCS selections for each target tile. Therefore, dark bars concern the following question: Are the inferred colourimetric parameters very different from the real ones?

The different values represented by the three light bars on the left of Figure 6 indicate maximal between-observer variability for chroma (Δ C*) and minimal for lightness (Δ L*), with chromatic angle (Δ H*) at an intermediate level. Friedman's analysis of variance indicates that there were significant differences among these three parameters. Wilcoxon tests indicate that there was higher variability for chromatic angle than for lightness (Δ H* vs. Δ L*, z = 2.053, p = .040). No other comparisons were statistically significant (Δ H* vs. Δ C*, z = 0.747, p = .455; Δ L* vs. Δ C*, z = 1.929, p = .054).

The values represented by the three dark bars on the right of Figure 6 are very similar. Friedman´s analysis of variance revealed no significant differences among the three parameters (ΔH*, ΔC*, ΔL*) in the discrepancy between the real colourimetric values and the inferred ones (χ^2 = 0.857, p = .651).

The following question remained: does the between-observer variability differ significantly from the variability between the real and the inferred colourimetric parameters? In order to respond to this, the light and dark bars represented in Figure 6 were compared, no differences were found, statistically significant, between all the possible comparisons between pairs of bars (ΔC*, z = 0.643, p < .520; ΔH*, z = 1.442, p < .149; ΔL*, z =1.234, p = .217; ΔE*, z = 0.191, p < .848).

DISCUSSION

The relevance of results shown in Figure 6 can be considered in two different ways. The first way requires using a standardised atlas to compute the colourimetric differences for very similar tiles. For example, using the information given at the end of the electronic appendix available in http://www.uv.es/psicologica and Equation (5), successive NCS atlas achromatic samples can be compared (N-0500 vs. N 1000; N 1000 vs. N 1500, etc.). As might be expected, taking into account the similarity of W' (NCS whiteness) and L* (CIE lightness), the chromatic variation (Δ E*, in this case, equal to Δ L*) between each pair of consecutive tiles has a mean value of 4.37 (SD = 1.25). Upon examining the three pairs of bars corresponding to C*, H*, and L* in Figure 6, one may conclude that the error corresponding to each of these parameters was very similar to the difference between two consecutive NCS achromatic tiles. Of course, when their combination is considered (Δ E*), the value is somewhat higher, although lower than the difference between two NCS achromatic tiles separated by ten whiteness units (for example, between N0500 and N1500). On the other hand, the value is very similar to the E* $\approx$ 8 that can be computed for two contiguous Munsell tiles[4] using the corresponding colourimetric measurements (see, for example, Travis, 1991, Appendix 1). Lastly, this value is much lower than the one that can be computed for the OSA tiles, because in this case, Δ E* $\approx$ 23.

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[4] The purpose of Munsell atlas is to have a similar and just discriminable difference between any pair of contiguous colour samples.

The second way of considering the relevance of the results shown in Figure 6 is to compare the tiles included in two classical tests within the framework of the evaluation of the ability to differentiate colours: the Farnsworth-Munsell 100 Hue Test (see Birch, 1993, p. 60) and the D-15 Test. In both tests, the correct response is represented by a coloured circle in which the most similar tiles are contiguous. The most important difference between the two tests is the value of the minimal colourimetric difference between two tiles. For the Farnsworth-Munsell 100 Hue Test, this is so small ($\Delta E^* < 3$) that most common observers make some errors when responding to the test. For the D-15 Test, it is larger (between 4 and 11) because the pattern of correct responses is meant to lead common observers towards a gradual and easily discernible transition in colour. Most important, the way in which the test was designed causes frequent categorical changes (for example, from blue to purple) in dichromats' responses. The ΔE^* value for such changes is about 40.

Taking all the above and the results shown in Figure 6 into account two conclusions can be reached. First, considering the variation between the real and the estimated values, both separately and for each chromatic dimension (C*, H*, and L*), the differences (Δ) were slightly higher than the minimal differences between the proximal tiles of the Farnsworth-Munsell 100 Hue Test and, on the other hand, exactly at the upper limit of the D-15 Test equivalent differences. The perceptual status of these differences can be described in the following colloquial terms: "slightly more than the minimum required to detect a small chromatic difference without errors." The second conclusion considers the conjoint effect (ΔE^*) of the three dimensions, represented by the pairs of bars located at the right of Figure 6. Because the values represented by these bars are clearly within the variability range corresponding to the D-15 Test for common observers and, at the same time, below that required for a clear change in chromatic category, their perceptual status can be described as follows: "small chromatic changes, easy to detect without errors."

GENERAL DISCUSSION

The results presented in this paper, including the electronic appendix available in http://www.uv.es/psicologica, are useful for researchers who wish to select stimuli rigorously and do not have access to sophisticated instrumentation. For example, if one wishes to create a set of stimuli with chromatism (C*) similar to the first tile described in the electronic Appendix (Y0502): (1) This must be introduced in a worksheet (for example, Microsoft Excel). (2) Using conventional equations (Lillo 2000, chap. 4), the stimuli most similar to the target could easily be selected.

Complementing the above paragraph, the close relationship between what the NCS refers to as hue and the chromatic angle (or dominant wavelength, see Figure 5) allow one to use Table 1 to select tiles on the basis of their chromatic angle. All that is needed is to look for the NCS hue nearest the desired angle.

When the goal is not to select tiles from the NCS atlas but, as we did in the second experiment, to use it to measure the colour of a group samples, the precision level obtained may be sufficient for many applied tasks, although it is, of course, inferior to the one that could be obtained using sophisticated instruments. In other words, matching samples with the most similar NCS tiles allows one to assign colourimetric values close to the correct ones, although perceptually differentiable from those values. Summing up, if, for example, one wishes to specify the colourimetric values of two stimuli to determine their contrast, the calculus performed by matching them with the most similar NCS tiles will be accurate and very similar to the best calculus possible. On the other hand, sophisticated colourimetric instrumentation must be used when exact colour reproduction (a very precise task) is desired.

In addition to the practical consequences of our research, we also reach an important theoretical conclusion. This is very much related to Figure 4 and can be stated as follows: Regarding surface colours, there is a close relationship between quantitative and qualitative aspects of stimulation, because some types of stimuli are only possible with certain reflectance values. In this context, the most noteworthy example appears in the proximity λ_D = 570 nm (H* = 84.85). Here, for dark stimuli (Figure 4.A), only low purity levels appear (no proximity to the diagram perimeter). In contrast, for medium and light stimuli, high purity stimuli also appear (Figures 4.B. to 4. G). Lastly, for very light stimuli, again only low purity levels are possible. In any case, we would like to emphasise that our results are in accordance with, and expand, those obtained over the last forty years (Judd, MacAdam, & Wyszecki, 1964; Maloney, 1986; Lennie & D'Zmura, 1988; Maloney & Wandell, 1986; Shaw, Westland, & Thompson, 1999) showing that, contrary to what is possible in laboratories, natural stimuli have important restrictions regarding the range of possible values in the colourimetric measurements.

In concluding, an important question remains. Based on our results, can the nomenclature of the Natural Colour System (NCS) be considered "natural"? The strong relationship detected between what the NCS refers to as "hue" and λ_D suggests that this is not the case. Let us see why.

Various publications (Boynton & Gordon, 1965; Gordon & Abramov, 1988; Nagy, 1980; Pridmore, 1999 a, 1999 b; Purdy 1931, 1937) have reported the existence of the Bezold-Brüke effect and the parameters that determine its strength. Briefly, it consists of a break in the hue-dominant wavelength relationship. Considering the Bezold-Brüke effect, it can be predicted that some NCS tiles, similar both in NCS hue denomination and in λ_D, must be perceived with different hues. Such a prediction can be directly evaluated presenting the NCS tiles for monolexemic (just one word) denomination. This kind of experiment has been carried out recently by our research group (Lillo et al., in preparation), obtaining many examples of responses in accordance with the Bezold-Brüke effect. For example, although the tiles Y0580 and Y4550 have the same NCS denomination ("Y", yellow), only the first one was called “yellow”. On the other hand, Y4550 was called green 60% of the times and, even more important, was never called yellow. In conclusion, the “Natural” Colour System atlas nomenclature appeared to be not so natural, because it does not agree with natural and spontaneous colour denominations.

RESUMEN

Reflectancia y Desequilibrio energético: Evaluación colorimétrica del atlas de color NCS. Se evaluó al atlas NCS de dos maneras. La primera se basó en una serie de mediciones colorimétricas exhaustivas (a las que se puede acceder mediante el apéndice electrónico que figura en http://www.uv.es/psicologica) y que fueron utilizadas para: (1) Relacionarlas con los parámetros descriptivos utilizados por el atlas, y (2) analizar las propiedades colorimétricas generales de los colores de superficie. El segundo tipo de evaluación examinó el resultado de usar el atlas NCS para especificar colorimetricamente muestras de color no pertenecientes a él. El análisis de las relaciones existentes entre el NCS con los parámetros colorimétricos mostró que cada matiz-NCS se asoció con un ángulo cromático específico y, consiguientemente, con una longitud de onda dominante. La relaciones existentes entre, por una parte, la blancura NCS y la claridad CIE y, por otra, entre los parámetros de croma CIE y NCS, fueron altas pero sin alcanzar niveles máximos. Cuando se consideró globalmente al atlas se observó que el nivel de claridad determinaba en gran medida la saturación y el ángulo cromático de los estímulos. Concretamente, para claridades bajas se observaron los niveles más altos de saturación CIE para los ángulos cromáticos asociados a cualquiera de los extremos del espectro o de la línea de los morados. Para claridades altas, por el contrario, se observaron los niveles más altos de saturación para los ángulos cromáticos relacionados con la porción media del espectro. El segundo tipo de evaluación del NCS consideró su posible utilidad para inferir los parámetros colorimétricos de muestras no incluidas en el atlas. Puesto que se detectó un nivel de error relativamente bajo ($\Delta E < 8$), se concluyó que el atlas puede utilizarse para aquellas aplicaciones prácticas que implican cálculos colorimétricos con un nivel de precisión medio o bajo.

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