Psicológica (2004), 25, 23-43.

Lightness and hue perception: The Bezold-Brücke effect and colour basic categories

Julio Lillo*[1], Luis Aguado*, Humberto Moreira*, and Ian Davies**

* Complutense University of Madrid

** University of Surrey

Using surface colours as stimuli, the present research was aimed at the two following goals: (1) To determine the chromatic angles related to categorical effects type B-B (Bezold-Brücke). (2) To determine the colourimetric characteristics compatible with each Spanish colour basic category. To get these goals the full set of tiles included in the NCS (Natural Colour System) was used in a monolexemic naming task. Results showed that the use of chromatic categories was not only influenced by chromatic angle (Hu'v') but also by saturation (Su'v') and lightness (L*). This last parameter had a decisive influence on the responses to half of the chromatic circle (from G50Y to R50B, in terms of NCS nomenclature). Specifically, frequent B-B type categorical effects appeared: stimuli with the same chromatic angle, but different lightness being named differently.

Our research integrates two research fields that, until now, have been unrelated: (1) The Bezold-Brücke effect (hereafter, the B-B effect) and (2) chromatic basic categories. This integration is possible because in both cases stimulus intensity variation produces hue perception changes. In our opinion, the relevance of this fact has been understated by the scientific-technological community. Following the prevailing opinion, hue perception should be strongly determined by dominant wavelength (see, for example, Sanders & McCormick, 1993, pg. 513) but only sligthly by stimulus intensity.

A B-B effect appears when stimuli similar in λ_D (dominant wavelength), but of different intensity, are perceived as different hues. Though this effect was discovered in the XIX century and was studied frequently during the XX century (for example, Haupt, 1922; Nagy, 1980; Pridmore, 1999 a; 1999 b; Takahashi & Ejima, 1983; Walraven, 1961), it has commonly been considered as "a second order phenomenon" (Boynton & Gordon,1965; pg. 78).

---

[1] This study was supported by the DGYCYT BSO2000-0743 and by the MECD AP-0575 grants. Correspondence should be addressed to Dr. Julio Lillo Jover. Departamento de Psicología Diferencial y del Trabajo. Facultad de Psicología. Universidad Complutense de Madrid. Campus de Somosaguas. 28223. Madrid (Spain). Tel: + 34 91 3943198. Fax: + 34 913942830. Email: julillo@psi.ucm.es.

In our opinion, the diffusion of Purdy's classical works is one of the main determinants of the almost exclusive role attributed to λ_D in the determination of hue perception. Two facts must be emphasised in this context. First: Purdy exclusively used *aperture colour*[1] to study the B-B effect. Second: his experimental procedure asked observers to adjust the wavelength of a monochromatic stimulus (adjusted stimulus) to make its hue similar to the other one (reference stimulus). The greater the difference between the wavelengths of adjusted and reference stimuli, the larger the B-B effect, because, by definition, the effect refers to the difference in hue between two stimuli that are equivalent in λ_D but of different intensity.

Purdy's method main inconvenient is that it does not provide directly usable information about the identity and relevance of the hue changes produced by the B-B effect. More specifically, although the procedure allows one to know when two stimuli of different wavelength and intensity are perceived as similar in hue, it offers no direct information about the hue identity nor about the type of the perceived hue change resulting from the variation in intensity. To obtain direct information about both aspects, a colour-naming technique (Boynton & Gordon, 1965; Gordon & Abramov, 1988) must be used.

When using a colour-naming technique to study the B-B effect, observers are usually required to identify the basic sensations (red, green, blue, or yellow) into which the experienced hue can be decomposed and, very important, their relative strength (for example, a response could be "30% red, 70% yellow"). Using colour-naming techniques, Boynton and Gordon (1965) and Gordon and Abramov, (1988) obtained results consistent with the most widely accepted description of the B-B effect (see, for example, Wyszecki, 1986), which was originally formulated by Helmholtz (1896) and can be stated as follows: Given a specific wavelength, the use of high-intensity levels enhances the blue or yellow components of the hue. The use of low-intensity levels enhances the green or red components.

As we have already noted, Purdy (1931; 1937) used aperture colours to study the B-B effect. With only two exceptions (Hunt, 1989; Pridmore, 1999a, part 2), all studies of the B-B effect done during the XX century have used these stimuli, instead of surface colours. Moreover, in former studies, Hunt and Pridmore used a relatively small stimulus-sample. Consequently,

---

[1] In the specialised literature (for example Kaiser & Boynton, 1996; pg. 39) a distinction is made between aperture and surface colours. The last correspond to the normal mode of colour perception, where colour apparently belongs to the surfaces of objects. Aperture colour results whenever the colour is presented in such a way as to make its localization impossible with respect to an object. One way to do this is with a "reduction screen" which permits a view of only a small part of a surface. Another way is using points of light in the darkness. Considering that no other information influences the perception of the aperture colours, these are sometimes named "unrelated colours". In contrast, surface colours are named "related colours", because their perception is influenced by the background stimuli.

concerning surface colours there isn’t enough information in relation to: (1) The $\square_D$ (or the chromatic angles) most affected by B-B effects and (2) their relevance. The research here reported is an attempt to provide such information.

Research done in the second half of the 20th century on chromatic basic categories (Kaiser & Boynton, 1996; Schirillo, 2001) used colour naming techniques to respond an essential question: Which are the colour terms consistently used by the speakers of a specific language? To answer this question, subjects must indicate the word (monolexemic naming task) most accurate to describe the chromatic experience produced by each of the presented stimulus. Because colour stimuli were commonly samples of a standardised chromatic atlas, obtained results were usually specified in terms of the atlas specific nomenclature (Boynton & Olson, 1987; 1990; Lin, Luo, MacDonald & Tarrant, 2001 a; 2001 b; 2001 c; Sturges & Whitfield, 1997), that can be easily “translated” to the one standardised by the CIE. Consequently, it is possible to know the $\square_D$ (or the chromatic angle) and the lightness (L*) of the tiles related to a specific basic category. Consequently too, it is easy to relate research on the B-B effect to research on chromatic basic categories.

Research done at California University at the end of the eighties by Boynton & Olson (1987; 1990) is relevant to our goals because, as ourselves, these authors used an extended stimuli sample to get a global impression about how basic categories are used in colour space. Thanks to it, they found that only two categories, blue and green, were compatible with all lightness levels (light, medium, dark). That the reverse were true for the other categories implicitly indicates the existence of important B-B effects, because it shows that for the same dominant wavelength stimuli different basic categories were used in response to different lightness.

Our research had three specific goals. The first two were related, more or less directly, to Boynton and Olson’s results. The first one was to specify which parts of the colour space are compatible with the use of a specific colour basic category in a specific language (English in their case, Spanish in ours). To make easier the comparison between our results with the ones usually obtained when studying the B-B effect, a specification in terms of CIE parameters and graphic representation was chosen. On the other hand, considering the results obtained in some studies using a restricted sample of colours (Davies, Corbett & Bayo, 1995), we predicted that the position that chromatic Spanish categories would occupy on the colour space should be essentially similar to those of their English counterparts.

Our second goal was to make explicit what was implicit in the work of Boynton and Olson: The specification of the chromatic angles where the categorical B-B effects appear. That is, the ones in which variation of stimulus intensity (lightness change) is associated with hue changes big enough to change the basic category used in the naming task. Also, based on the results of Boynton and Olson, it was predicted that this result would be concentrated on the wavelength range associated with the basic categories with restrictive lightness range (all, except green and blue).

Our third goal was to evaluate the nomenclature of the atlas that provided the surface colours we used: The NCS (Härd, Sivick, & Tonnquist, 1996 a; 1996 b; SIS, 1996). This atlas is a very accurate choice considering the previously mentioned goals, because a previous colourimetric evaluation (Lillo, Moreira & Gómez, 2002), has shown a direct correspondence between what the atlas refers to as "hue" and the stimuli $\square_D$. Consequently, if contrarily to our expectations, there were no categorical B-B effects, and if the NCS-hue denomination really corresponded to the hues actually experienced by normal observers, all the tiles with a specific NCS-hue denomination should receive the same colour term. Otherwise, the accuracy of the NCS nomenclature would be in question.

METHOD

Participants. Nine subjects (six females and three males) took part in the experiment. They were between 24 and 42 years of age (mean 27.22; standard deviation 5.95). All were screened for normal colour vision by means of the Ishihara Pseudo-Isochromatic colour plates, the City University Color Vision Test (CUCVT; Fletcher, 1980), the "Test para Identificación de los Daltonismos" (TIDA [Test to Identify Colour-Blindness]; Lillo, 1996), and Rayleigh matches on an anomaloscope. All the observers had previous experience in colour-naming tasks.

Stimuli and apparatus. Stimuli to be named were the 1795-tile set contained in the NCS index (SIS, 1997). This version was selected because its stimuli (henceforth, tiles) afford easy colourimetric measurement and are easy to use in naming tasks. The tiles are 2 x 5 cm arranged in 212 numbered rectangular (29 x 5 cm) bands of from 2-9 tiles.

The NCS system assumes that the hue of any colour can be defined in terms of its similarity to the four chromatic elemental sensations (red, green, yellow, and blue) and, consequently, it postulates four hue scales: The Y-R (from yellow to red), the R-B (from red to blue), the B-G (from blue to green), and the G-Y (from green to yellow). One, and only one hue scale, must be used to specify the hue corresponding to a specific tile, in addition to a number between zero and one hundred. The lower the number, the more similar is the hue of the tile to that corresponding to the letter on the left of the NCS denomination (for example, B10G represents a slightly greenish blue). Contrariwise, high numeric values are used to indicate higher similarity to the hue corresponding to the letter on the right (for example, B90G represents a slightly bluish green). Previous research (Lillo et al., 2002) has revealed an almost perfect correspondence between the NCS-hue denominations and $\square_D$. Table 1 specifies the $\square_D$ corresponding to each NCS-hue. It also shows the corresponding chromatic angles (H*u'v'; see Hunt, 1987) for each $\square_{D.}$

Table 1. Dominant wavelength (λ_D.) and chromatic angle (H*u'v') for each NCS-hue.

NCS Denomination	λ_D	H*u'v'	NCS Denomination	λ_D	H*u'v'
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

When presented in the naming task, the stimuli measured 2 x 2 cm and were binocularly observed at a distance of 40 cm, projecting a visual angle of 2.8 degrees. The stimuli were presented on a medium-grey (N 5000; L*=50%) background. All the photometric and colourimetric measurements were performed by a Photoresearch PR-650 connected to a PC computer. To avoid discontinuities in the illuminant spectral distribution, fluorescent lamps were avoided. Instead, incandescent lamps of 3630 K (275.5 MR) provided light that, using Rosco corrective filters, reached a correlated colour temperature of 5754 K (173.8 MR). The tiles were observed inside a booth that provided the aforementioned illumination after passing through a diffuser filter. The illuminance on the tiles was between 225 and 250 luxes. The booth structure and the angle between the observer and the tile prevented glare. This observation conditions where identical to the ones used to measure the tiles foto-colourimetrically.

Procedure. Two random orders were created to present the 1795 NCS tiles two times for each observer. Each tile was observed binocularly for three seconds, after which its colour had to be named using one of the following

Spanish basic terms: *azul* [blue], *verde* [green], *amarillo* [yellow], *rojo* [red], *naranja* [orange], *morado* [purple], *marrón* [brown], *blanco* [white], *negro* [black], and *gris* [grey]. The interstimulus interval was two seconds.

To enhance continuous task attention, the observers were allowed to interrupt the task whenever they felt tired or less motivated. Due to this, there were inter-observer differences in session duration (between 1/2 and 2 hours), number, and the number of breaks.

RESULTS

We first analyse the data to see which terms are used consistently and for which tiles. We then explore how the use of consistent terms changes across lightness levels for constant NCS hues. We define a response as consistent if more than half of responses across subjects to a given tile were the same (9 or more of 18 responses). Out of the 1795 NCS tiles, 172 did not produce response consistency and 318 were consistently named with an achromatic term (51 white, 240 grey, 27 black). On the other hand, 1305 tiles were consistently named with chromatic categories (207 blue, 400 green, 94 yellow, 44 red, 101 orange, 75 purple, 161 pink, and 223 brown). Unless otherwise indicated, all analyses were restricted to this group of 1305 chromatic tiles.

Table 2 shows the most important naming-task results. Its first column indicates the NCS-hue denomination. Columns two, three, and four show the basic terms used consistently as responses to at least one NCS tile. The second column is identified as "light" because it refers to tiles with lightness equal or over 65 ($L^* \geq 65$; real range between 65 and 93.51). The third column is identified as "medium" because the lightness is between 65 and 45 ($65 > L^* \geq 45$). The fourth column is identified as "dark" because lightness was always less than 45 ($45 > L^*$; real range between 15 and 45). By separating the tiles according to these ranges, we were able to divide the 1795 NCS tiles into three sets that were very similar in number. Specifically, there were 572 light tiles (498 named consistently), 628 medium tiles (577 named consistently), and 595 dark tiles (547 named consistently).

In Table 2, the fifth column shows a number indicating the variation in naming categories for each NCS-hue. If, as in the case of "B" or "R80B" the same responses appear for all three L* levels, then a "zero" (0) variation value was computed. If, as in the case of "B50G" or "B30G," there were either changes between the light and medium naming categories, or between these and the dark ones, then a "one" (1) variation value was computed. Lastly, as in the case of "Y" or "Y20R," a "two" (2) variation value was computed when the categories changed from light to medium and from medium to dark. Columns 5 and 6 only differ in that, in the latter, pink and red were computed as equivalent (no inter-variation) categories.

Figure 1 presents the results of the two right-hand columns of Table 2 graphically. The combined light and dark region represent the results from column 5. The light region corresponds to column 6. The diameter extending from G50Y to R50B divides the colour circle into two semicircles that differ in naming consistency. For the lower one, most variation values equal zero. The exception to this pattern are the NCS denominations ranging from B30G to B50G, where the value one appears because blue tends to be used for the light stimuli and green for the dark ones.

A very different situation from the one just described applies to the upper semicircle of Figure 1. Now, the predominant presence of grey indicates high variation levels, especially for the range between Y20R and Y80R. As can be seen, there is only a small change in the variation values when red and pink are considered equivalent or non-equivalent categories (column 5 and 6, respectively, of Table 2).

Until now, table 2 has been used to determinate the variation values corresponding to each NCS-Hue (see figure 1). In our next analysis, the mean variation values corresponding to each category were used. These values were obtained by averaging the values from column 5 of Table 2 corresponding to all the NCS-hues where a specific term was used. For example, for the blue category, the values corresponding to the NCS-hues between R60B and B50G were averaged. Two groups of categories can be formed, considering these mean variation levels. The first group only included the two categories with minor variation level: Blue (0.3) and Green (0.65). The second group included the rest of the categories. More specifically, Yellow (1.55), Red (1.5), Orange (2), Purple (1), Pink (1.7) and Brown (1.7). A series of Mann-Whitney tests indicated that there were no significant differences in the mean variation values between the two categories of the first group (Blue and Green; $U = 66$; $p = .276$) nor between those of the second group ($p > .05$ for all possible comparisons between pairs of categories). On the other hand, these latter categories differed significantly from both blue ($p < .003$) and green ($p < .025$). The purple category was the only exception to this pattern, because it was not significantly different from blue ($U = 9.5$; $p = .091$) nor from green ($U = 25$; $p = .382$). The only significant difference for purple was when it was compared to orange ($U = 3$; $p = .018$), the category that produced the maximum variation level.

Figure 2 shows the stimuli named consistently with a chromatic term differentiated according to L*. In addition to the chromaticity diagram perimeter, it presents an irregular contour that indicates the area occupied by all the NCS tiles. This contour defines an area that, from now on, will be called the “NCS colour area.” At its centre, a white square indicates the position of the illumination used (achromatic point, u’ = 0.194; v’ = 0.484). Concentrating on the NCS colour area facilitates understanding how the atlas tiles change their chromatic positions depending on L*.

Table 2. Terms used consistently for each NCS-hue denomination and lightness level. Columns five and six indicate how categories change as a function of lightness. (0 = no change. 1 = change between one pair of lightness contiguous levels. 2 = change between the two pairs of lightness contiguous levels.

NCS Denomination	**Light $L^* \geq 65$**	**MEDIUM $65 > L^* \geq 45$**	**Dark $L^* < 45$**	**Variation**	**Variation if Pink = Red**
G50Y (567 nm)	**Ye, Gre**	**Gre**	**Gre**	**1**	**1**
G60Y	Ye, Gre	Gre	Gre	1	1
G70Y	Ye	Bro	Gre,Bro	2	2
G80Y	Ye,Bro	Bro	Bro	1	1
G90Y	Ye,Bro	Bro	Gre,Bro	2	2
Y(576 nm)	Ye	Ye,Gre	Gre,Bro	2	2
Y10R	Ye	Bro	Bro	1	1
Y20R	Ye,Or	Or,Bro	Bro	2	2
Y30R	Ye,Or,Bro	Or,Bro	Bro	2	2
Y40R	Or	Or,Bro,Pi	Or, Bro	2	2
Y50R(594 nm)	**Or,Pi**	**Or,Bro,Pi**	**Or, Bro**	**2**	**2**
Y60R	Or,Pi	Or,Bro	Or, Bro	1	1
Y70R	Pi	Red,Or,Bro,Pi	Red,Bro	2	2
Y80R	Pi	Red, Bro,Pi	Red,Bro	2	1
Y90R	Pi	Red, Bro,Pi	Red,Bro,Pi	1	1
R(629 nm)	Pi	Bro,Pi	Red,Bro	2	1
R10B	Pi	Pi	Red,Bro,Pi	1	1
R20B	Pi	Pi	Red,Bro,Pi	1	1
R30B	Pi	Pur, Pi	Pur,Bro	2	2
R40B	Pur, Pi	Pur	Pur	1	1
R50B(-549 nm)	**Pur**	**Pur**	**Pur**	**1**	**1**
R60B	Blue, Pur	Blue, Pur	Blue, Pur	0	0
R70B	Blue	Blue	Blue	0	0
R80B	Blue	Blue	Blue	0	0
R90B	Blue	Blue	Blue	0	0
B(485 nm)	Blue	Blue	Blue	0	0
B10G	Blue	Blue	Blue	0	0
B20G	Blue	Blue	Blue	0	0
B30G	Blue	Blue	Blue,Gre	1	1
B40G	Blue	Gre	Gre	1	1
B50G(494 nm)	**Blue,Gre**	Gre	Gre	**1**	**1**
B60G	Gre	Gre	Gre	0	0
B70G	Gre	Gre	Gre	0	0
B80G	Gre	Gre	Gre	0	0
B90G	Gre	Gre	Gre	0	0
G (512 nm)	Gre	Gre	Gre	0	0
G10Y	Gre	Gre	Gre	0	0
G20Y	Gre	Gre	Gre	0	0
G30Y	Gre	Gre	Gre	0	0
G40Y	Gre	Gre	Gre	0	0

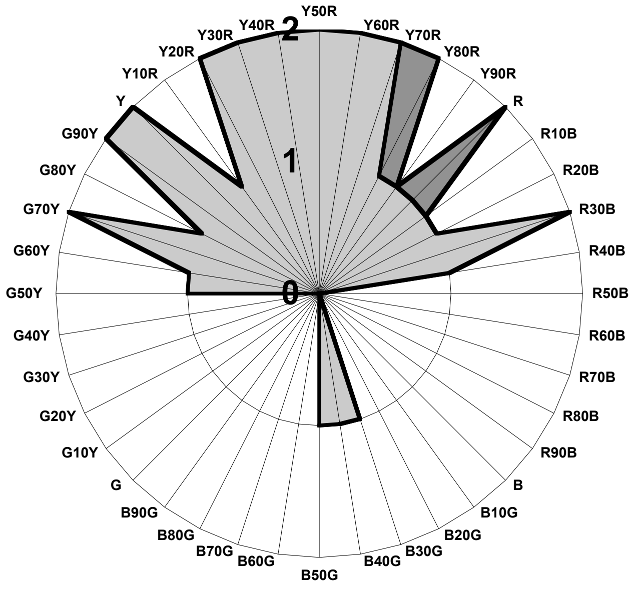


Figure 1. Lightness and variation among categories. When shaded area extends from "0" to "1," changes were detected only between two contiguous lightness levels. When extending to "2," there were changes between all the contiguous lightness levels.

The points presented in Figure 2A correspond to dark stimuli ($L^* < 45$) and, taken conjointly, cover practically the entire NCS colour area. This is not the case for medium (Figure 2B) and light (Figure 2C) stimuli, because as L^* increases, the portion of the NCS colour area covered becomes progressively restricted. More specifically, 2B shows a gap in the lower portion of the NCS colour area (dominant wavelengths of spectrum extremes and purple line). This gap is larger in Figure 2 C, because most of the light tiles are concentrated near the dominant wavelength corresponding to the NCS " Y " (Yellow, 576.5, represented by a line ending in a triangle) and to a lesser degree "B" (Blue 495.8 nm, a line ending in a square).

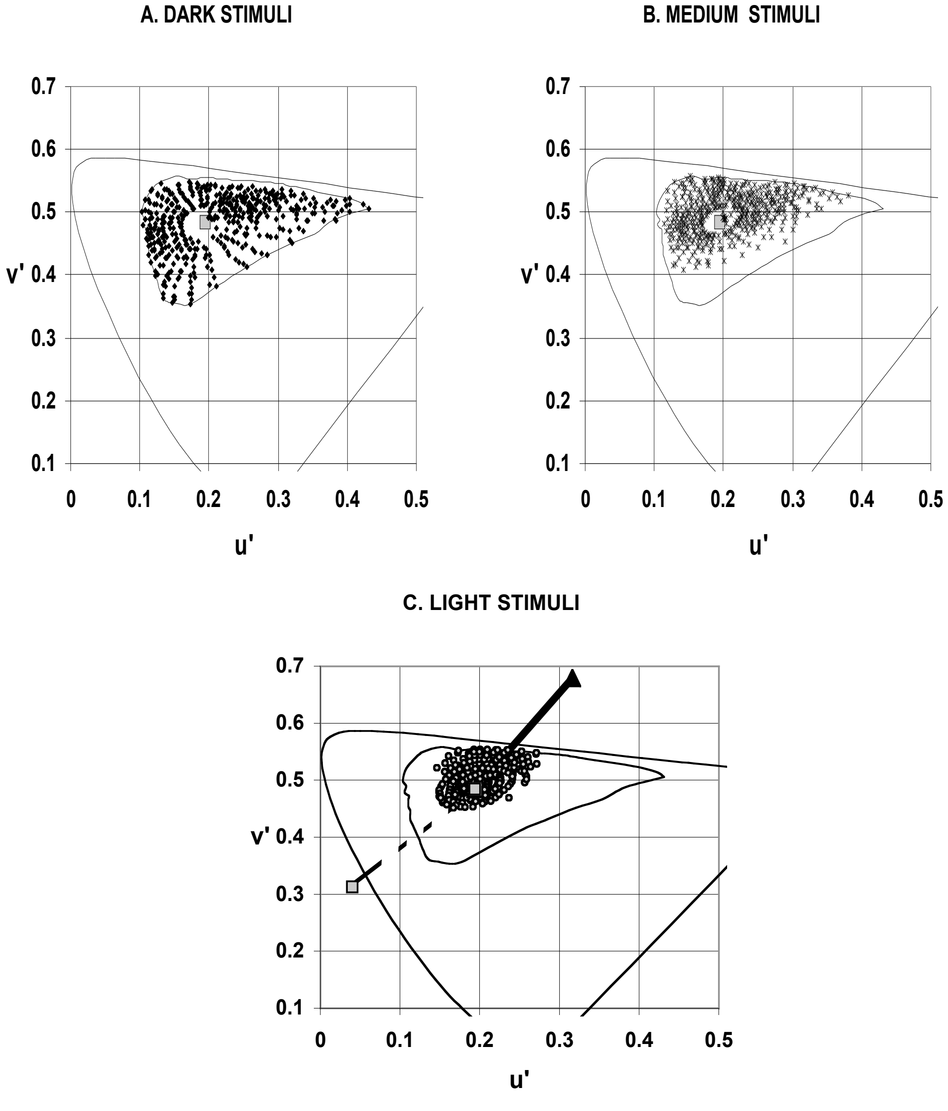
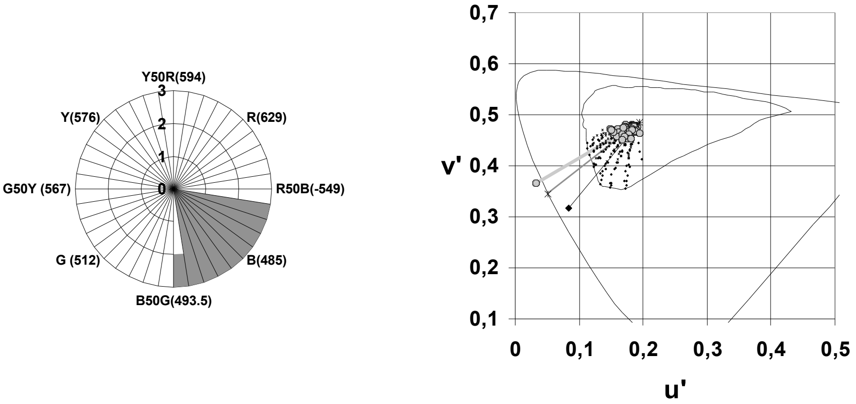
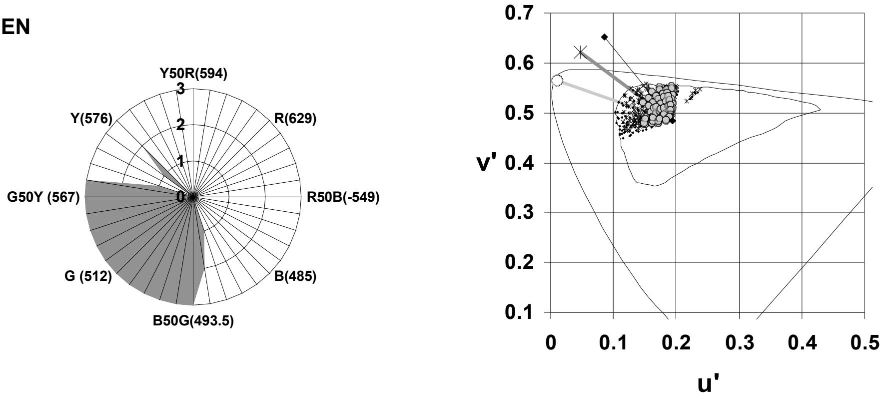


Figure 2. Chromatic co-ordinates of the tiles named consistently with a chromatic category. (A) Dark stimuli. (B) Medium stimuli. (C) Light stimuli.

BLUE



GREEN



YELLOW

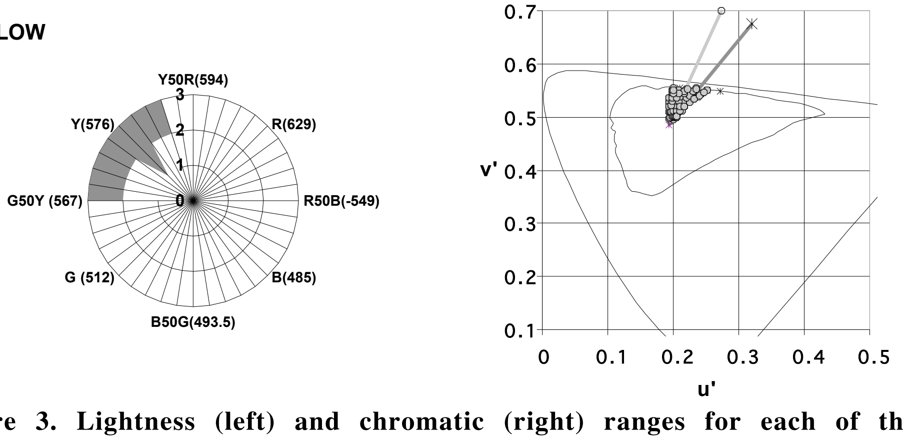
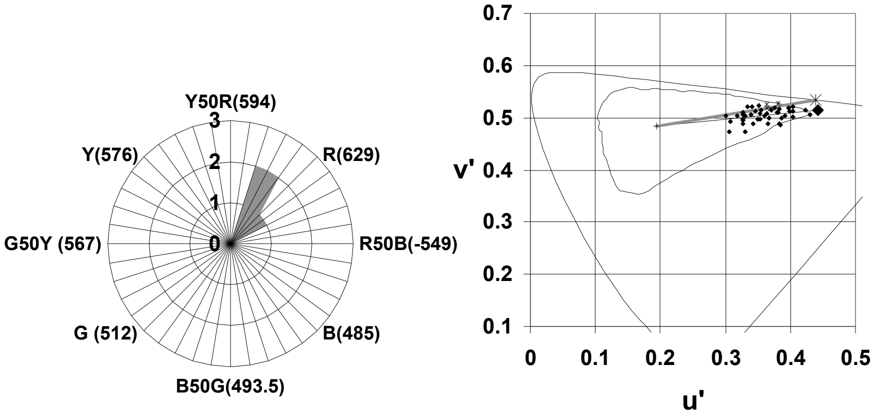
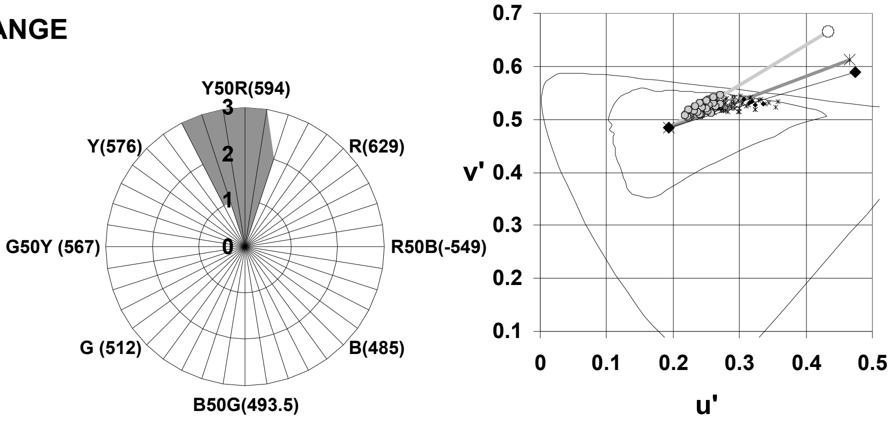


Figure 3. Lightness (left) and chromatic (right) ranges for each of the eight Spanish basic categories. Left columns. The shadowing in the circles indicates if a category was used in response to dark (from 0 to 1) medium (from 1 to 2) and light (form 2 to 3) tiles. Right columns. Every point in each chromacity diagram correspond to a stimulus belonging to the indicated categories. Lines indicated mean chromatic angle for light (line ended with O) medium (line ended with∗) and dark (line ended with ◆) stimuli.

RED



ORANGE



PURPLE

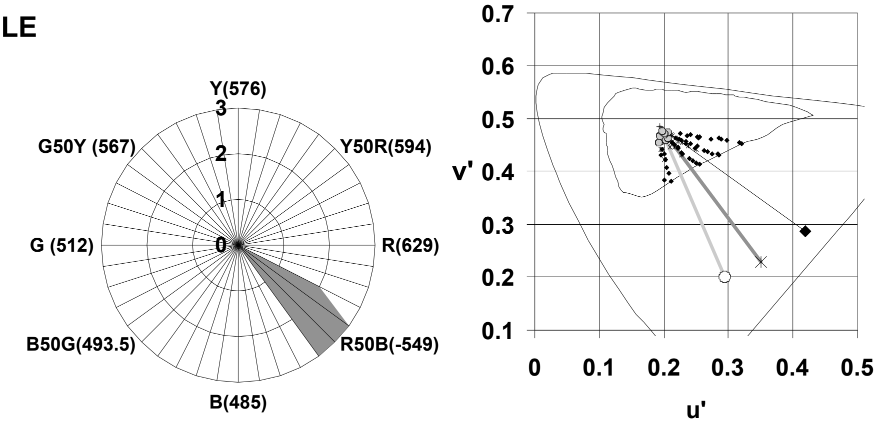
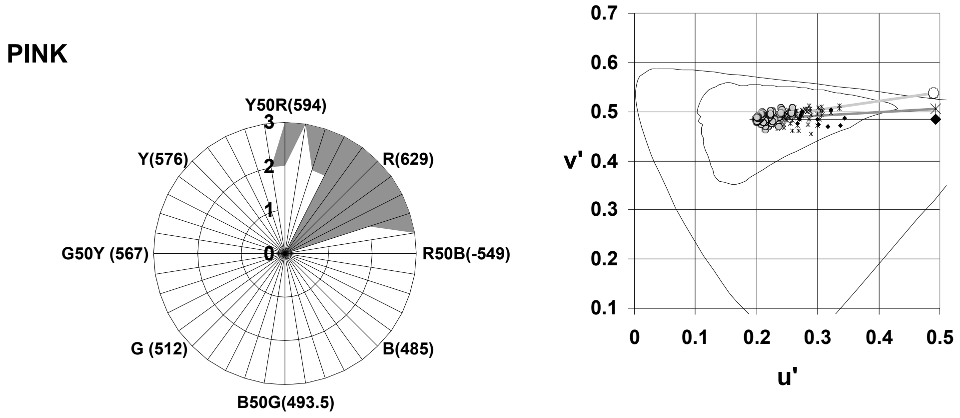


Figure 3 (cont.).



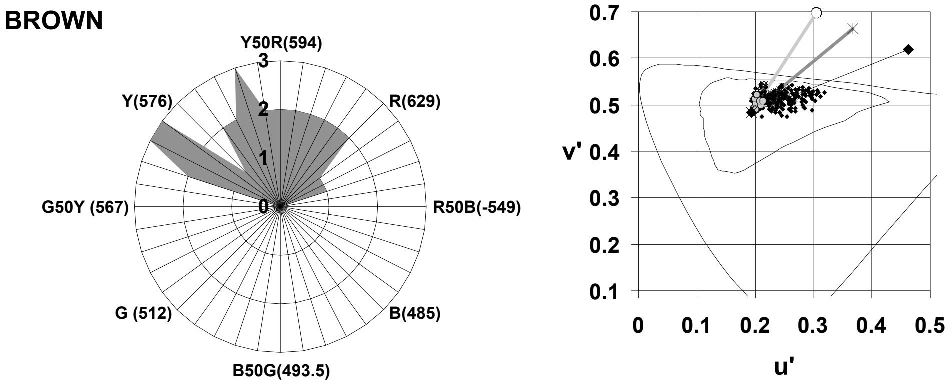


Figure 3 (cont.).

The different parts of Figure 3, in combination with Tables 3 and 4, provide exhaustive information about changes in the use of each chromatic term due to lightness variation. The circles on the left side of Figure 3 show which NCS-hues produced the use of a basic term in at least one NCS tile, and at which L* levels. Specifically, circles with the numbers 1, 2, and 3 are used to indicate L* level. A shaded area between the values of 0 and 1 indicates that the category is used for the dark tiles. If the shaded area is between 1 and 2, the category is used for the medium tiles. If the area between 2 and 3 is shaded, then the category is used for the light tiles. A few examples will show how the shaded areas between circles should be interpreted. The circle presented at the upper left on Figure 3 shows that, for most of the NCS-hues that produced the response of "blue," the shaded area extends uninterruptedly from 0 to 3. Consequently, it can be concluded that this term is used almost equally for all three L* levels. In the circle corresponding to "yellow", almost all the NCS-hues present a shaded area only between 2 and 3. Consequently, it can be concluded that this basic term was used mostly for light stimuli.

Table 3. Mean chromatic angles for each chromatic category and lightness level. Column five indicates the type of change produced by the increase in lightness.

Category	Lightness Level			CHANGE TYPE
	Dark	Medium	Light	
Blue	236.52	224.23	216.13	Clockwise
Green	122.81	136.86	165.96	Counter-clockwise
Yellow	--------	56.59	69.87	Counter-clockwise
Red	06.86	11.54	-------	Counter-clockwise
Orange	20.57	25.24	37.05	Counter-clockwise
Purple	318.64	301.49	289.46	Clockwise
Pink	359.84	4.14	10.27	Counter-clockwise
Brown	26.69	46.19	62.49	Counter-clockwise

Table 4. Frequency (in brackets) and relative percentage of tiles consistently named with a chromatic term for the three levels of lightness (dark, medium, and light).

Category	**Dark**	**Medium**	**Light**	**Total frequency**
Blue	(90) 43.48%	(70) 33.82%	(47) 22.71%	(207)
Green	(137) 34.42%	(170) 42.46%	(93) 23.11%	(400)
Yellow	--------	(6) 6.38%	(88) 93.62%	(94)
Red	(40) 90.91%	(4) 9.91%	--------	(44)
Orange	(5) 4.95%	(62) 61.37%	(34) 33.66%	(101)
Purple	(45) 60.00%	(22) 29.33%	(8) 10.67%	(75)
Pink	(9) 5.55%	(80) 49.69%	(72) 44.72%	(161)
Brown	(138) 61.68%	(74) 33.18%	(11) 4.93%	(223)

The diagrams to the right of Figure 3 show the chromatic positions for the tiles consistently named with a chromatic basic term. Information about the relationship between L* and chromaticity is provided in two ways. First, different symbols are used to identify the dark (black rhomboids), medium (black asterisks), and light (grey circles) tiles. Second, several lines (maximum, three) were drawn to indicate the mean chromatic angle for the dark (dark line ending in a rhomboid), medium (grey line ending in an asterisk), and light (light line ending in a circle) stimuli. Table 3 specifies the value of this parameter and the type of change produced in their position by the increase in L*. For two categories, blue and purple, the change is clockwise. For the rest (green, yellow, red, orange, pink, and brown), the change is counter-clockwise. These changes can be described as a movement towards one of the two lines of Figure 2C. In the case of red, orange, pink, and brown, the increase in L* causes the mean chromatic angle to draw nearer to the "Y" (Yellow) NCS-hue. In the case of green and purple, the change is toward the "B" (Blue) NCS-hue.

Table 4 complements Figure 3 in an essential aspect, providing information about the number of tiles (frequency, in brackets) that received a term as a function of their L*, and their relative percentage (compared to all the tiles that received that term). This information does not appear on the circles of Figure 3 for reasons of legibility. Having clarified the interpretation of Figure 3 and Tables 3 and 4, we can now summarise the most important results for each specific category.

Participants used *azul (*blue) between the NCS-hues R60B ($\square_D$ = 400 nm; H*u'v' = 279.49) and B50G ($\square_D$ = 493.5; H*u'v' = 190.88). Although this term was used more frequently for low L*, there was a large number of "blues" at all three L* levels.

Participants used *verde (*green) between the NCS-hues B30G ($\square_D$ = 489; H*u'v' = 205.40) and Y ($\square_D$ = 576.5; H*u'v' = 59.75), but discontinuously in the NCS-hue G80Y. Although this category was used frequently in response to stimuli with any of the three L* levels, the circles in Figure 3 and Table 4 show that it was used less frequently for lighter stimuli. More specifically, there were no light greens for the NCS-hues B30G, B40G, G70Y, G90Y, and Y (see circles in Figure 3) and there were fewer light greens than medium or dark greens (see Table 4).

"Yellow" was used between the NCS-hues G50Y ($\square_D$ = 566.5; H*u'v' = 96.94) and Y30R ($\square_D$ = 588.0; H*u'v' = 29.85) and was used almost exclusively for light stimuli. That is, as displayed in the circle of Figure 3, only one (Y) of the 9 NCS-hues associated with the yellow category was applied to medium L*. Complementarily, Table 4 shows that only 6 yellow stimuli (6.38%) out of 94 were considered to be of medium L*.

"Red" was used between the NCS-hues Y70R ($\square_D$ = 602.5; H*u'v' = 13.01) and R20B ($\square_D$= □498.5; H*u'v' = 354.29). With regard to L*, red can be considered the opposite of yellow. That is, for all the indicated NCS-hues, there were "red" denominations for dark stimuli but, as seen in the circle of Figure 3, only three NCS-hues produced red at medium L*. Moreover, these three hues only accumulated 9,91% of the tiles named red consistently (see Table 4). Lastly, the diagram corresponding to red in Figure 3 reveals a peculiarity for this category: the absence of exemplars near the achromatic point (u = 0.194; v' = 0.484).

"Orange" was used between the NCS-hues Y20R ($\square_D$ = 583.0; H*u'v' = 39.86) and Y70R ($\square_D$ = 602.5; H*u'v' = 13.01). It was employed for high and, preferentially, medium L* stimuli (only 5 dark tiles were named orange). According to this preference, only medium L* produced orange responses for Y70R (see Figure 3), and the percentage of medium oranges (61.37%) was much higher than the light ones (33.66%), as is shown in Table 4.

"Purple" was used between R30B ($\square_D$ = □502.5; H*u'v' = 343.33) y R60B ($\square_D$ = 400; H*u'v' = 279.49). Its L* range is more restricted than indicated in Figure 3 (only R30B does not produce full shading), because Table 4 indicates that is much more compatible with low (60%) than with high (10.67 %) L*.

Participants used "pink" between the NCS-hues Y40R ($\square_D$ = 590.5; H*u'v' = 24.94) and R40B ($\square_D$ = □523.; H*u'v' = 328.02) and applied it preferentially to medium (49.69%) and light (44.72%) tiles. Figure 3 shows that the pink category tends to be used for unsaturated stimuli (near the achromatic point, u' = 0.194; v' = 0.484). In this respect, pink is the opposite of red.

"Brown" was used in the colour-circle portion delimited by the NCS-hues G70Y ($\square_D$ = 570; H*u'v' = 84.85) and R30B ($\square_D$ = □502.5; H*u'v' = 343.33). Because this term is used essentially to name dark stimuli (61.68 %), it looks less extensive in Figure 3 (the inner circle, from 0 to 1 in Figure 3, takes up less space).

DISCUSSION

In addition to the previous paragraphs, Figure 3 and tables 2, 3 and 4 give an exhaustive information related to our first goal: to get a precise specification of colour space parts compatible with the use of a specific colour basic category in Spanish. This specification was made in terms both of NCS specific nomenclature (table 2) and of the CIE standards (figure 2; tables 3 and 4). In addition to its inherent value, this information makes obvious that the colourimetric specification of a basic category can not be made only in terms of dominant wavelength, but must also include lightness and saturation. Very important, and confirming what was previously noted by Boynton and Olson (1987, 1990), it was observed that, with the exception of the blue and green categories, the other chromatic basic terms had a restricted lightness range. This is easy to appreciate in Figure 3, because most of the shadowed areas do not extend from the centre to the perimeter.

Our second goal was to make explicit what was implicit in some studies related with the use of colour basic categories: The specification of the chromatic angles where the categorical B-B effect appears. That is, the ones in which the stimulus intensity variation (lightness change) is associated with hue changes big enough to change the basic category used in the naming task. Figure 1 shows that, in this respect, the colour circle can be divided in two hemicircles, being the upper one the more susceptible to these type of effects. More specifically, the observed relationships can be summarised as follows: (1) The colour circle can be divided into four quadrants, resulting from the intersection of the lines G50Y-R50B and Y50R-B50G. (2) In the case of the

G50Y-Y50R quadrant, the use of “yellow” and “orange” predominates for the light stimuli, with “green” and “brown” being the most commonly used categories for the dark stimuli. On the other hand, for the Y50R-R50B quadrant, “pink” is predominant in response to light stimuli, but “red” and “brown” play a similar role for the dark stimuli. (3) In the case of the two lower quadrants, the use of basic terms is not very much affected by L*. This result was predicted, considering that these quadrants are related to blue and green. In the case of the R50B-B50G quadrant, “blue” is the predominant category, and in the case of the B50G-G50Y quadrant, “green” plays an equivalent role. (4) In the case of the dominant wavelengths related to the transition from blue to green (B30G-B50G), L* determines to a great extent which one is used preferentially. Specifically, “blue” is predominant for light stimuli and “green” for the dark ones.

The pattern of results described in the previous paragraph has important similarities to what is commonly observed when the B-B effect is studied using aperture colours (see, for example, Boynton & Gordon, 1965; Gordon & Abramov, 1988). Specifically, the way in which stimulus intensity influences participants’ preference for “blue” or “green” in response to some dominant wavelengths (those indicated in the previous paragraph) or, similarly, their preference for “yellow” and “green” in the G50Y-Y50R quadrant (yellow for light stimuli, green for dark ones), was also reported by them and can be explained assuming the relative dominance of the yellow-blue mechanism over the red-green one for light stimuli (and the opposite for dark ones).

It is very instructive to compare our results with the ones recently obtained by Lin et al. (2001 a; 2001 b; 2001 c), using a smaller stimuli sample of surface colours. Specially relevant in this respect are figures 2 and 3 of Lin et al (2001c), that show that even when the same chromatic angle is maintained, reducing L* may produce a change of category, from orange to brown (Figure 2) or from yellow to green (Figure 3), which is entirely consistent with what is indicated in table 2 of the present paper. However, and contrary to what the mentioned figures might suggest, our results indicate that these category changes are not an unavoidable consequence of the reduction of L*, because the exemplars of each pair of categories are not coincident in the number and identity of the NCS denominations to which they are applied. For example, while the yellow category was consistently used to designate the lighter tiles of the NCS hues in the range between G50Y and Y30R, green was only applied in this same range to darker stimuli with NCS hues between G50Y and Y.

There are important differences with regard to red and yellow between our results and those obtained using aperture colours (see Ayama, Nakatsue, & Kaiser, 1987; Larimer, Krant & Cicerone, 1974; 1975; Pridmore, 1999 a; 1999 b; Vos, 1986). Specifically, in the cited studies, these two categories were used in response to the whole range of intensities employed (for example, from 10 to 2000 td, in Vos, 1986; from 0.1 to 1000 cd/m^2 in Pridmore 1999a). Table 4 shows a very different pattern of results that is more in accordance with Boynton and Olson (1987; 1990): for the NCS tiles, there was a strong relation between the intensity parameter and the way both terms were used. Over 90% of the stimuli named as “yellow” were light stimuli and the opposite was true for the stimuli named as “red” (90,91% of these were dark stimuli).

The expression “stimulus intensity” has a different meaning, depending on whether aperture or surface colours are used. In our opinion, this explains the differences in the use of the red and yellow categories mentioned in the previous paragraph. Briefly, intensity parameters related to aperture colours (cd/m^2 or trolands) are absolute values, because they only depend on the quantity of energy transmitted to the eye. However, the intensity parameter for surface colours (L*) is relative, because it is the result of weighting the quantity of energy sent by a surface in relation to the energy corresponding to the rest of the environment. That is, a light surface is not just a stimulus that sends a lot of energy (high luminance) to the eye, but a stimulus that sends more energy than most of the other stimuli from the same environment. Considering this, one can posit that the strong dependence on L* found for red and yellow depends on different factors. We shall now examine the reasons for this.

As seen in the red chromaticity diagram in Figure 3, it can be concluded that this category is incompatible with low levels of saturation. Therefore, in order to produce the perception of red, the light reflected by a surface must fulfill two requirements: (1) it must have a medium-high saturation level and, therefore it must accumulate energy in a relatively narrow range of wavelengths. (2) These wavelengths must belong to the long spectrum extreme. Considering the low luminous power of the wavelengths associated with use of the red category, it can be predicted that red surfaces must have reduced L*. Of course, this limitation does not affect stimuli such as the headlights of a car, which are based on emission of light, but not on reflectance.

The tentative explanation of the relationship between high L* and yellow is very different. As can be observed on the appropriate colour circle of Figure 3, and in contrast with the case of red, the yellow category is compatible with every saturation level. On the other hand, as can be observed from the position of the line ending in a triangle in Figure 2C, there are stimuli with $\square_D$ similar to the best yellows, with low (Figure 2A), medium (Figure 2B), and high L*. Why then did over 90% of the yellow tiles have high L*? More specifically, if the NCS tiles Y0570 and Y4550 have virtually the same chromatic co-ordinates (x = 0.44; y = 0.46), then why is only the former named yellow? (Y4550 was called green). The answer could be that, although both stimuli send the same kind of stimulation to the retina, the (relatively) low amount of light sent by Y4550 allowed activation of some inhibitory mechanisms that are not operative in response to Y0570. Of course, this explanation is speculative and the present results are not conclusive enough to this respect.

The third goal of our research was to evaluate the accuracy of the NCS (Natural Colour System) hue nomenclature and, considering the previously reported (Lillo, Moreira & Gómez, 2002) strong relation existing between it and dominant wavelength, this nomenclature only could be accurate if no categorical B-B had been detected in our research. As figure 1 makes explicit, our results were no concordant with this expectative and, as table 2 specifies, stimuli with the same NCS hue denomination were often named differently. For example, the dark stimuli identified as "yellow" by the NCS were consistently named as "green" or "brown" by our observers. Considering this type of inconsistencies, it can be concluded that the NCS in not really a "natural" system to denominate colours. Moreover, concerning surface colours, the B-B effect is a "first order phenomenon" as it shows that perception of hue depends on lightness as much as on dominant wavelength.

RESUMEN

Claridad y percepción del matiz: El efecto Bezold-Brücke y las categorías cromáticas básicas. La investigación se efectuó en el ámbito de los colores de superficie y tuvo las dos siguientes finalidades: (1) Determinar los ángulos cromáticos asociados a la aparición de efectos categoriales tipo B-B (Bezold-Brücke) (2) Delimitar las características colorimétricas compatibles con el uso de cada categoría cromática básica del Español. Para alcanzar los objetivos indicados se empleó el conjunto de fichas contenidas en el atlas NCS, como fuente de estimulación en una tarea de denominación monolexémica. Los resultados mostraron que la utilización de las categorías cromáticas básicas no sólo dependen del valor del ángulo cromático (Hu'v') sino también del de la saturación (Su'v') y la claridad (L*). La importancia de este último parámetro fue especialmente relevante para, aproximadamente, la mitad del círculo cromático (de G50Y a R50B en la nomenclatura NCS). Ante esta mitad se dieron frecuentes efectos categoriales tipo B-B y, por tanto, estímulos semejantes en ángulo cromático, pero diferentes en claridad, recibieron denominaciones diferentes.

REFERENCES

Ayama, M., Nakatsue T. & Kaiser P. K. (1987). Constant hue loci of unique and binary balanced hues at 10, 100 and 1000 td. *Journal of the Optical Society of America, 6,* 1136-1144.

Berlin, B. & Kay, P. (1969). *Basic Color Terms: Their universality and evolution.* Berkeley: University of California Press.

Boynton, R. M. & Gordon, J. (1965). Bezold-Brücke shift measured by color-naming technique. *Journal of the Optical Society of America, 55,* 78-86.

Boynton, R. M. & Olson, C. R. (1987). Locating Basic Colors in the OSA Space. *Colour Research and Application, 12,* 94-105.

Boynton, R. M. & Olson, C. X. (1990). Salience of chromatic basic color terms confirmed by three measures. *Vision Research, 30,* 1311-1317.

Corbet, G, G. & Davies, I. R. L. (1997). Establishing basic colour terms: measures and techniques. In: C. L. Hardin & L. Maffi. *Color categories in thought and language* (pp. 197-223). Cambridge: University Press.

Davies, I. R. L., Corbet, G. G. & Bayo, J. (1995). Colour terms in catalan: an investigation of eighty informants, concentrating in the purple and blue regions. *Transactions of the Philological Society. 93.* 17-49.

Fletcher, R. J. (1980). *The City University Color Vision Test (2nd Ed).* London: Keeler.

Gordon, J. & Abramov, I. (1988). Scaling procedures for specifying color appareance. *Color Research and Application, 13,* 146-152.

Härd, A., Sivick, L. & Tonnquist, G. (1996). NCS, Natural Color System-from concept to Research and Applications. Part 1. *Color Research and Application, 21,* 180-205.

Härd, A., Sivick, L. & Tonnquist, G. (1996). NCS, Natural Color System-from concept to Research and Applications. Part 2. *Color Research and Application, 21,* 206-220.

Haupt, I. A. (1922). The selectiveness of the eye's response to wavelength and its change with change of intensity. *Journal of Experimental Psychology, 5,* 347-379.

Helmholtz (von), H. (1896). Handbuch der Physiologischen Optik. (2nd Ed.). Hamburg. Voss.

Hunt, R. W. G. (1987). *Measuring Colour*. New York: Wiley.

Hunt, R. W. G. (1989). Hue-shifts in unrelated and related colours. *Color Research and Application*, *2*, 55-68.

Kaiser, P. K. & Boynton, R. M. (1996). *Human color vision (2nd Ed).* Washington, DC: Optical Society of America.

Larimer, J., Krantz, D. H. & Cicerone, C. M. (1974). Opponent process additivity I: Red/Green equilibria. *Vision Research, 14,* 1127-1140.

Larimer, J., Krantz, D.H. & Cicerone, C.M. (1975). Opponent process additivity II: Yellow/blue equilibria and nonlinear models. *Vision Research, 15,* 723-731.

Lillo, J. (1996). *Manual del test de identificación de daltonismos (TIDA).* Madrid: TEA.

Lillo, J., Moreira, H. & Gómez, N. (2002). Reflectance and energetic imbalance: Colorimetric evaluation of NCS colour Atlas. *Psicológica. 23,* 209-232.

Lin, H., Luo, M. R., MacDonald, L.W. & Tarrant, A. W. S. (2001 a). A cross-cultural colour-naming study. Part I: Using an unconstrained method. *Color Research and Application*, *26*, 40-60.

Lin, H., Luo, M.R., MacDonald, L.W. & Tarrant, A. W. S. (2001 b). A cross-cultural colour-naming study. Part II: Using a constrained method. *Color Research and Application*, *26*, 193-208.

Lin, H., Luo, M.R., MacDonald, L.W. & Tarrant, A. W. S. (2001 c). A cross-cultural colour-naming study. Part III: A colour-naming model. *Color Research and Application*, *26*, 270-277.

Nagy, A. L. (1980). Short-flash Bezold-Brücke hue shifts. *Vision Research, 20,* 361-368.

Pridmore, R.W. (1999 a). Bezold-Brucke hue-shift as functions of luminance level, luminance ratio, interstimulus interval and adapting white for aperture and objects colors. *Vision Research, 39,* 3873-3891.

Pridmore, R.W. (1999 b). Unique and binary hues as functions of luminance and illuminant color temperature, and relations with invariant hues. *Vision Research, 39,* 3873-3891.

Purdy, D.(1931). Spectral hue as a function of intensity. *American Journal of Psychology, 43,* 541-559.

Purdy, D. (1937). Bezold-Brüke phenomenon and contours for constant hue. *American Journal of Psychology, 49,* 313-315.

Sanders, M.S;., & McCormick, E.J. (1993). *Human Factors in Engineering and Design: Seventh Edition*. New York. McGraw –Hill.

SIS (1996). *Standardiseringen I Sverige Swedish Standards Institution: Atlas 96*. Stockholm. Scandinavian Colour Institute.

Schirillo, J.A. (2001). Tutorial on the importance of color in language and culture. *Color research and application, 26,* 179-192.

Sturges, J, & Whitfield, A. (1997). Salient features of Munsell colour space as a function of monolexemic naming and response latencies. *Vision Research*, *37*, 307-313.

Takahashi, S., & Ejima, Y. (1983). Functional relationship between chromatic induction and luminance of inducing stimulus. *Journal of the Optical Society of America, 73,* 198-202.

Vos, J.J. (1986). Are unique and invariant hues coupled? *Vision Research, 26,* 337-342.

Walraven, R.L. (1961). On the Bezold-Brüke phenomenon. *Journal of the Optical Society of America, 51,* 1113-1116.

Wyszecki, G. (1986). Color appeareance. In K.R. Boff., LL. Kaufman & J.P. Thomas (Eds). *Handbook of Perception and Human Performance*. New York. Wiley.

(Manuscript received: 31 May 2002; accepted: 7 May 2003)