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Original Contributions - Originalbeiträge

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# The white and black colour attributes in the Natural Colour System

## Introduction

In this research white and black are studied from the phenomenal point of view recommended by Hering (1920). Hering also dealt with physiological aspects of colour vision, but still today his phenomenal analysis remains unmatched. The distinction between phenomenal and physiological viewpoint is relevant because the observer is aware of what he sees, not of the underlying physiological processes of vision. Not only experimental phenomenology deals with the appearance, but it adopts relationships between appearances as explicative variables.

Hering showed that great deal of research can be performed on colour vision without studying the physical and physiological background. These aspects are *very* important but belong to another field of study, which is not essential to the phenomenal investigation, like the one performed here.

Unfortunately, in the past colour science was almost only interested in the underlying physical and physiological processes, also because of the limited methodologies, then considered acceptable (psychophysics), and therefore the fortune of the phenomenal point of view by Hering remained unknown for a long time. Only after Hurvich and Jameson (1957) discovered and studied the opponent cells which were considered responsible for the opponent visual characteristics of colours, did Hering's theory start to be known and appreciated. But the evaluation was motivated mainly by the neurophysiological processes which were thought to be the true core of Hering theory.

These physiological grounds, which see in neuron opponency the basis of the phenomenal opponency, despite important arguments against it (Valberg 2001) are the reason why this aspect of colours is still nowadays considered the main characteristics of the natural colour system. On the other hand the description of perceptually mixed and unmixed colours made by Hering seems to be of secondary significance, while it introduces a great and relevant simplification in the field of colour analysis. Unmixed colours, also named either unique, or elementary, or simple colours (the term primary usually refers to the physical components of a mixture), are those which do not resemble any other colours, while all the remaining colours show some resemblance, more or less pronounced, to not more than four unique ones. The common operational definition of unique colour is "neither … nor …", for instance a particular red is unique if it resembles neither yellow nor blue (of course it cannot be similar to green, which is opponent to red). The conclusion is that there are six unique colours (yellow, red, blue, green, white, and black), of which four are chromatic (yellow, red, blue, green) and two achromatic (white and black). All colours can appear similar to white and black, while the chromatic mixed colours can be similar to only a couple of unique chromatic colours, those not opponent.

The novelty and greatness of Hering's analysis on colour perception is in the phenomenal side which has been considered so important today to inspire a new colour system, already foreseen by Hering (1907, Chapter 2), who named it Natural Colour System. Here natural means that it is in the nature of colours in being perceived as we perceive them. That is, everybody perceives colours in the same way, with the same unique colours and the same opponent pairs. Often Hering is misunderstood in the sense that unique colours might differ from person to person (expressions like this are frequent: 'the colour I perceive as unique green you perceive as unique blue'). The mistake is that the colour is not a physical stimulus (; there is a general agreement that the same stimulus can initiate the perception of different colours: see metamerism, colour constancy, and so on), but colour is what we perceive. Therefore, if two people perceive a unique red (coeteris paribus, i.e. with the same nuance), they perceive the same colour, independently of the physical substrate.

In the past many researchers undertook the task of devising and achieving a colour system inspired by Hering ideas (Ostwald 1917, Johansson 1937, Hesselgren 1954, Hård 1965, and lastly Hård, Tonnquist, and Sivik 1996a, 1996b) and today the enterprise accomplished by the last three researchers materialized in the NCS®© (Natural Colour System) widely used and diffused all over the world.

The starting point in the production of the NCS has been an innovative concept by Hering (1920) according to which a mixed colour can be described by evaluating how much it resembles only one of the two it resembles. The key idea is that if the similarity to one colour increases, the similarity to the other colour decreases, so that the interval between the two reference colours represents a bipolar scale (Figure 1). The novelty of this idea is better understood in the case of all greys which are similar to both white and black, in different proportion. The identification of a grey therefore is not based on a concept of *intensity* (more intense stimulation higher lightness, less intense stimulation lower lightness) which is common to most colour systems (white would be the most intense achromatic colour, black would be the least intense achromatic colour, in parallel with

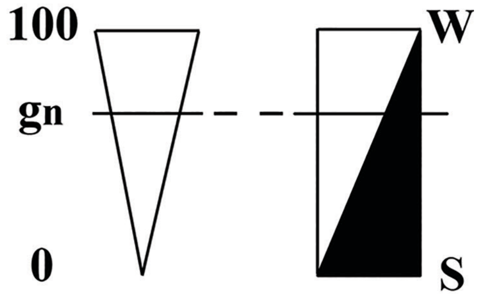


**Fig. 1.** On the left the traditional representation of a lightness scale, from 0 (minimum) to 100 (maximum); on the right the Hering white-black bipolar scale (in terms of similarity), from 0%W_100%S to 100%W_0%S. *gn* a specific grey.

the physical stimulation) but on the concept of similarity to white and black. In this case white and black are unique achromatic colours which do not resemble any other colours, and are well known to everybody without further specification (Berlin & Kay, 1969).

According to Hering (1920) colour attributes are not quantitative (representing physical intensity) but qualitative, that is purely phenomenal subjective appearance, and therefore, still according to Hering, cannot be directly quantified as performed in physics: on the contrary similarity can be quantified in percentage. The measure of a specific grey $g_n$ will traditionally be Munsell Value=6.0 in lightness, but under the Hering suggestion it will be 40% similar to black and 60% similar to white on the W-S bipolar scale. In the actual NCS colour notation – N 40 – only the similarity with black is reported, to stress that the criterion of similarity, and not of intensity, is used as for all the other aspects of colours: hue and chromaticness).

The first aspect of colours which is usually noticed and described is hue, and for this reason the first step in elaborating a measure of colours concerns hue. Analogously to the White-Black bipolar scale inside which all greys are numerically described in terms of percentage of similarity to white and black (the extremes of the scale), also in the case of hues their description in NCS is in terms of percentage of similarity with the extremes of a bipolar scale. Therefore, for example, the position of an orange in the Yellow-Red scale (Figure 2) depends on how much it resembles the two extremes (in the NCS the conventional direction is Yellow® Red® Blue® Green, while in the Munsell system the direction is reversed starting from red). If a specific orange is 45% similar to yellow it will necessarily be 55% similar to red, and the relative notation will be Y55R. For the achromatic (neutral) colours one does not need to specify the extremes of the bipolar interval, which are inevitably White and Black, while for the mixed hues one has to report to which extremes the colours appear similar.

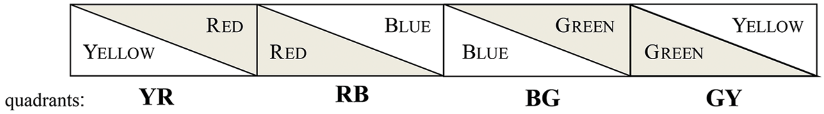


**Fig. 2.** A representation of all the hues according to Hering: unique hues (Y, R, B, G) and mixed hues are all inside the four bipolar scales. A property of this kind of bipolar scale is that the presence of the first hue decreases while the presence of the second hue increases.

## Construction of the present NCS

First step. The procedure used by Hård, Tonnquist, and Sivik (1996a) to build the current NCS system starts with the specification of the similarity of an achromatic colour (a grey) to white and black. The observer is asked to evaluate, in percentage by direct estimation, the similarity of a specific grey to white and to black under the condition that the two numbers sum up to 100. This restriction derives from theoretical reasons supported by observational experience. Our research (experiment 6) will show that it can be defined as an experimental result.

Second step. Once the hue of a colour has been preliminary specified, one needs to specify its *nuance*. This term in Hering (1920) means the different shades that colours of the same hue can show. The nuances differ as a function of the similarity with white and black; that is colours of the same hue can be more whitish (closer to white), more blackish (closer to black), more chromatic (closer to the full hue of the colour, neither whitish nor blackish). As the bipolar scaling is used to define the hue, to define the nuance one needs a *tripolar* scale to evaluate the three similarities involved in the nuance. Hence the observer has to report three numbers which express the similarity of the colour with white, black, and the pure most chromatic colour, in such a way that the three numbers sum up to 100. The three numbers can be represented in a *nuance* triangle in the form of distances from the three vertices representing the White the Black and the full colour (Figure 4).

Third step. The observer has to describe the hue of the given colour, by expressing with numbers its similarity to the four unique hues, again under the conditions that all numbers sum up to 100. As expected, nobody in the work by Hard et al. (1996a) used more than two numbers, assigned to pure hues consecutive in the hue circle (thus avoiding to quantifying the similarity to the opponent hues). The results can be visualized in the hue circle (Figure 3).

A particular colour with hue R50B would be placed in the intersection of the three lines (Figure 4) if it is similar to white for 25%, similar to black for 15% (and consequently, similar to a full R50B for 60%).

The full notation of the given colour represented in the triangle of the nuances will be 2560R50B, which should be read as a colour whose nuance is slightly blackish (25% similar to black), quite chromatic (60% similar to the full hue), and its *hue is* similar to blue for 50% and similar to red for the remaining 50%. This way of defining a colour is very useful because it refers only to the six unique colours which are very well known to everyone, and allows fast identification

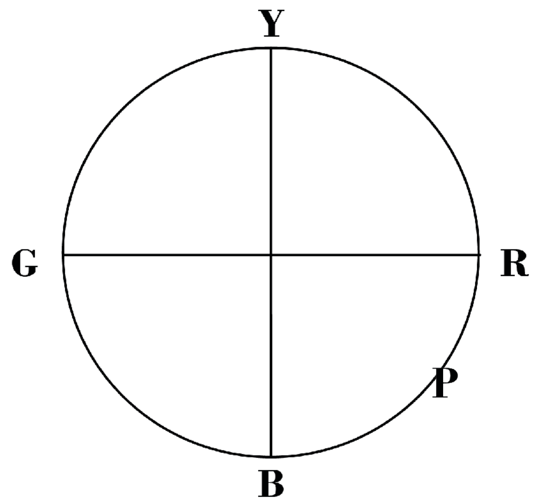


**Fig. 3.** Another more common representation of the hue circle. Each quarter of the circumference is a bipolar scale identified by its extremes. Purple (P) is a mixed colour and its place is therefore inside the red-blue interval.

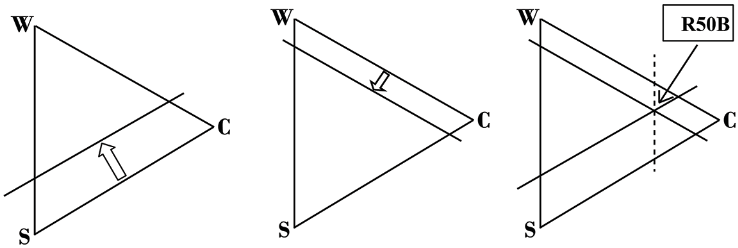


**Fig. 4.** Triangles of the nuances according to the present NCS. The *arrow* in the left triangle shows the *whiteness* of a nuance: all nuances along the side S-C (black – maximum chroma) show no similarity to white. The *length* of the arrow corresponds to the percentage of similarity to white: all nuances along the line pointed by the arrow show the same similarity to white (about 25% here). The *arrow* in the central triangle shows the *blackness* of a nuance: all nuances along the side W-C (white – maximum chroma) show no similarity to black, while all nuances along the line pointed by the arrow show the same similarity to black. The *length* of the arrow corresponds to the percentage of similarity to black (about 15% here). The vertical dashed line in the right triangle shows the *chromaticness* of the nuance, in this case 60% (distance from the achromatic W-S side). Its distance from the achromatic W-S side is determined in the present NCS by the similarity of the colour to white and to black evaluated to sum up to 100% with the chromaticness (intersection of the lines representing whiteness and blackness).

of the main perceptual attributes of the colour. The NCS system describes all colours as they are subjectively perceived without reference to physical stimuli. One can say that the description of a colour is independent of illumination and context because it refers only to what we see, not to how our colour perception is physically and/or physiologically determined. This knowledge is achieved in different sciences (mostly in current *colour science*).

The three steps procedure used by Hård, Tonnquist, and Sivik (1996a,1996b) to build the current NCS system has been described in detail because we used a different procedure, apparently very similar, but on more careful inspection it might show differences the strong relevance of which is evidenced in this paper.

This research has been accomplished inside a framework in which we wanted to elaborate a CRI (colour rendering index) in a more precise and efficient way compared with the standard CIE 1931 method (CIE 1995; Nickerson, 1965). In the CIE case one computes the colour differences (DeltaE) of a number of standard coloured surfaces which may appear different under different illuminations. The smaller differences between the two conditions (the standard and the test illumination) the higher the CRI, the larger differences the less CRI (Schanda 2005). We expected that by increasing the colour attributes to be visually evaluated the relevant differences introduced by test illuminations would be more detailed and accurate. The project involved the evaluation of *four aspects* of colours (similarity to white, black, and two appropriate unique hues), instead of the more common three hue, Value, and chroma, and then compute the differences in the evaluations under two illuminations.

## Experimental section

We present here some experimental research carried out with the aim of putting the new colour attribute evaluation method to the test. While the original procedure implemented by Hård, Tonnquist, and Sivik (1986a) to build the current NCS was simplified and concentrated in two steps, namely the determination of the hue of a colour in a *bipolar scale* (Sivik, 1974) and the specification of its nuance in a *three polar* scale (a triangle), with our method all four colour attributes had to be evaluated independently in four steps (evaluation of whiteness, blackness, redness, and blueness [or other suitable pairs of hues]). This more analytical procedure implied by independent evaluations was directed at producing a more detailed evaluation of a colour so that one can more easily detect relevant colour differences introduced by different illuminations. Compared with other procedures, for instance that used by Munsell, this seems to be a more direct method to describe phenomenologically, and at the same time quantify, the most relevant attributes of a colour.

## Materials

A *viewing box* was built in order to change easily the illumination of the colour samples. The interior (73 cm large, 52 cm deep, 53 cm high) was white and the exterior black. On the top different sources of light were located, hidden to the observer, who could only accede to the knobs controlling the actual illumination inside the box.

In this research we used one LED source (LED_D65), and a filtered halogen lamp producing an A illuminant (CIE standard, about 2800K, Table 1).

Sixteen *coloured cards* of four different hues (purple, turquoise, lime, orange) and four different nuances (1- a very chromatic one; 2- a whitish one; 3- a greyish one 4- a blackish one) were printed specifically for the experiment (Table 2; Figure 5 and 6).

**Table 1.** Colorimetric characteristics of the light sources used in the experiment. d. = declared; m. = measured.

| | | | | 8 CIE samples | | 14 CIE samples | |
|---|---|---|---|---|---|---|---|
| ***source*** | **d. CCT (K)** | **m. CCT (K)** | **d. Ra** | **m. RA** | **SD** | **m. RA** | **SD** |
| **A** | 2856 | 2856 | 100 | 99 | 0,2 | 99 | 0,5 |
| **LED1** | 6350-7000 | 6831 | 75 | 73 | 12 | 67 | 28 |

**Table 2.** The NCS notation of the sixteen experimental colours. Whiteness has been added for explicitness although redundant. In bold the prominent attributes of the colours.

| | S | C | hue | W | No. |
|---|---|---|---|---|---|
| Purple | 30 | **55** | R50B | 15 | 13 |
| | 20 | 30 | R50B | **50** | 15 |
| | 40 | 30 | R40B | 30 | 4 |
| | **50** | 40 | R50B | 10 | 7 |
| Lime | 5 | **60** | G50Y | 35 | 6 |
| | 5 | 30 | G50Y | **65** | 3 |
| | 20 | 60 | G50Y | 20 | 1 |
| | **50** | 30 | G50Y | 20 | 16 |
| Turquoise | 10 | **50** | B50G | 40 | 11 |
| | 10 | 20 | B70G | **70** | 9 |
| | 20 | 40 | B50G | 40 | 12 |
| | **40** | 30 | B50G | 30 | 10 |
| Orange | 10 | **70** | Y60R | 20 | 5 |
| | 20 | 20 | Y50R | **60** | 8 |
| | 30 | 30 | Y30R | 40 | 2 |
| | **50** | 30 | Y60R | 20 | 14 |

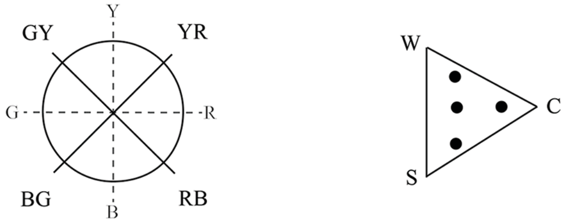


**Fig. 5.** The four GY, YR, RB, BG hues (*left*) and the four nuances (*right*) used in selecting the colours of this experiment.

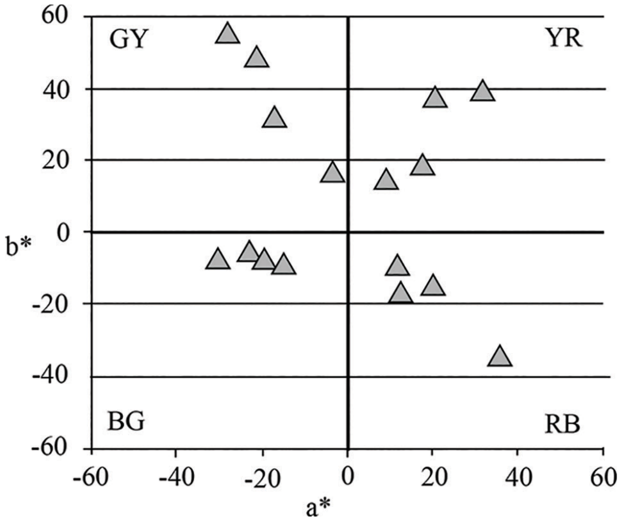


**Fig. 6.** The 16 experimental colours plotted in a CIELAB diagram.

The procedure for printing the experimental samples was subdivided in three steps: once the choice of the colours was determined according to table 2, each colour was prepared in Photoshop by referencing to a database provided by Claudio Oleari in which all the 1750 colours of NCS Atlas were measured by the spectrophotometer of his laboratory (University of Parma, personal communications. This database can be consulted on request to the author of this paper, but cannot be made public). Then the L*a*b* specifications of the colours were used to print the provisional samples in semi-gloss photography paper by an Epson Stylus Photo 2000P A3 inkjet printer. The printed samples, placed inside the viewing booth and illuminated by a D65 source, were then measured by a calibrated Konica Minolta spectrocolorimeter CS200, and the results compared with the measures of the data base. In case of deviations some corrections were introduced in Photoshop and new printed samples were achieved, until correct results were obtained (within a tolerance of ±1 in L*, a*, b*). A final check was performed by a NCS Colour Meter (2000) which shows the closest NCS notation of the test colour.

The coloured cards were bent to appear as a half cylinder (5,5 cm high, 4,5 cm diameter) and mounted on a white polystyrene frame. This layout was chosen to stress the perceptual difference between surface colour and illumination and favour the identification of the surface colour while 'discounting' the illumination. The variation in illumination is clearly distinguished from what remains constant in the stimulation, i.e. the surface colour, according to the well-known Gestalt principle of decomposition into common (illumination) and specific (object colour) factors proposed by Koffka (1935), Musatti (1957), Bergström (1977).

In test 2 and in test 6 we also used a series of 16 grey cylinders (5,5 cm high, 4,7 cm diameter; Munsell Value: 9.5, 9, 8.5, 8, 7.5, 7, 6.5, 6, 5.25, 5, 4.25, 4, 3.25, 3, 2.5, 1.75) placed on a portable white wooden tray (40 x 6 cm). They were printed by the same procedure described for the chromatic colours, keeping as reference the transformation formula from V (Value) to Y (reflectance factor) proposed by Newhall, Nickerson and Judd (1943). Then they were put in the viewing box in order of lightness from the darkest on the left to the lightest on the right for evaluations of whiteness, and the reverse for evaluations of blackness.

In test 5 48 colours were used (Figure 7), 12 from each NCS quadrant (their NCS notation in Table 3) all printed according to the same procedure described above.

We registered the subjective evaluations of colour attributes without using words or numbers, but only by a visual spatial length using *a 30 cm long slider.* An arrow, perpendicular to the small tube where it was mounted, could be moved by hand

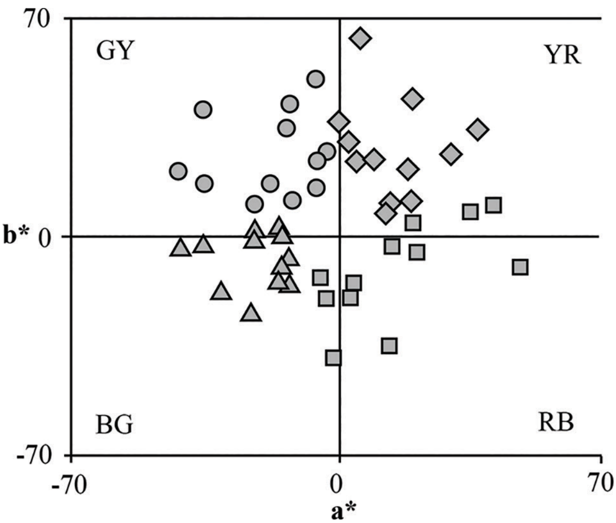


**Fig. 7.** The 48 colours used in test 5 are potted in a CIELAB diagram. Circle: 12 green-yellow colours; diamond: 12 yellow-red colours; square: 12 red-blue colours; triangle: 12 blue-green colours.

**Table 3.** NCS notation of the 48 colours used in experiment 5, divided in 4 hue quadrants of 12 colours each. The choice was made to obtain a wide distribution of colours in each quadrant (Figure 6).

| | BG | GY | YR | RB |
|---|---|---|---|---|
| 1 | 6020B90G | 1030G70Y | 4030Y90R | 3060 R10B |
| 2 | 2020B90G | 3050 G70Y | 1030Y10R | 3050 R10B |
| 3 | 1030B70G | 6020G30Y | 1060Y70R | 1060 R30B |
| 4 | 5030B30G | 5030G10Y | 4030Y10R | 4030 R30B |
| 5 | 1060B10G | 3060G90Y | 2020Y90R | 5030 R10B |
| 6 | 1030B10G | 1060G30Y | 3060Y30R | 6020 R30B |
| 7 | 3060B30G | 2020G90Y | 5030Y30R | 6020 R70B |
| 8 | 4030B10G | 4030G30Y | 6020Y90R | 1030 R70B |
| 9 | 2020B30G | 6020G70Y | 1030Y70R | 5030 R90B |
| 10 | 3050B70G | 3060G10Y | 1060Y10R | 3050 R70B |
| 11 | 3060B70G | 3050G10Y | 2020Y30R | 2020 R90B |
| 12 | 4030B90G | 5030G90Y | 3050Y70R | 3060 R90B |

from left to right and back of the slider, and then positioned in a point defining a specific visual length from the beginning. The left margin corresponded to the minimum value (0%) and the right margin to the maximum value (100%), both well visually evidenced. The direction *minimum left to maximum right* was congruent with the SNARC-like effect (Fumarola et al, 2014). This scale is not bipolar as happens in the NCS, but monopolar from a minimum 0% up to 100% (intensity scale).

After participants expressed their evaluation by deciding where to place the arrow of the slider, the experimenter read its position in terms of centimetres from the beginning, written on a paper strip hidden from the participant. That position was later transformed in percentage of the whole length.

### Test 1

The test was aimed at measuring the whitish and blackish appearance of the 16 experimental chromatic samples observed under two light sources (A and LED_D65). The hypothesis was to reproduce the nominal notations of the Natural Colour System (NCS) and check potential differences due to the illumination.

### Participants

**Four** psychology female students, 22-25 years old, with normal colour vision (checked by Ishihara test) volunteered in the experiment.

## Procedure

The cylinder-like coloured samples were put one at a time on the centre of the white floor of the light booth and the participant's task was to evaluate its whiteness (or blackness) by means of the described slider. Each participant made twelve evaluations for each condition (except one who performed only nine trials).

## Results

First of all, the subjective evaluations of the whitish (W) and blackish (S) appearance (Figure 7) were slightly but significantly different under the two light sources ($t(15)= 2{,}131$ , $p < 0{,}05$). On the other hand W and S were also correlated ($r= -0.951$). This result (Figure 8) shows that the procedure can be usefully used to build a CRI by keeping separated the attributes of colours to be assessed (here only W and S).

One absolutely unexpected result was that the sum of the subjective Ws and Ss were constant for all colours and at the maximum level (around 100%). These results (Figure 9) are incompatible with the present NCS structure, in which all colour attributes, both chromatic and achromatic, sum up to 100%. If the achromatic W and S already sum up to 100%, there is no room for the chromatic aspects as defined in the NCS (Figure 4).

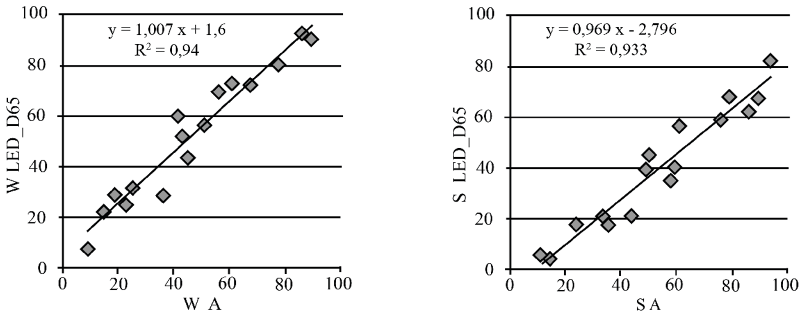


**Fig. 8.** Whiteness and blackness evaluations under the two A and LED_D65 light sources. Left: subjective evaluations of whiteness (W) under LED_D65 light as a function of W under A light. Right: subjective evaluations of blackness (S) under LED light as a function of S under A light.

It seems that our procedure leads to a different structure of the NCS. Nevertheless, developing our method to determine chromaticness, one can add a third step, not present in the procedure used by Hard et al. (1996a), in which the observer has to evaluate the similarity of the test colour to the grey previously found (by assessing its whiteness, or blackness).

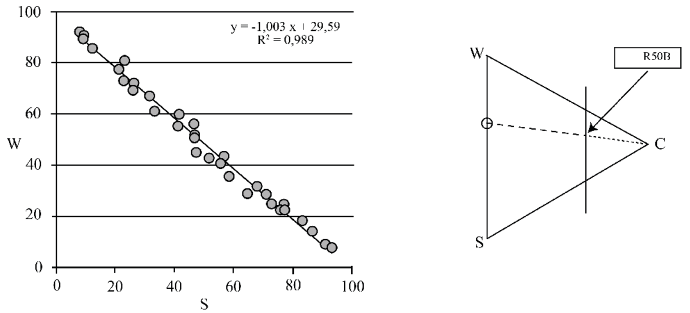


**Fig. 9.** *Left*. Subjective evaluations of whiteness (W) as a function of subjective evaluations of blackness (S) under both lights. *Right*. The dotted line would correspond, in a new way of looking at the NCS, to colours similar to the grey indicated by the circle, that is the grey determined by the similarity of the test colour to white (or to black). The arrow would show the position of the nuance in the triangle independently assessed. The perceived degree of similarity to that grey, that is the length of the thick segment (distance from the grey), will determine the chromaticness of the colour.

## Test 2

This test was aimed to check whether a different evaluation method might give rise to the same results. Here the participant had to identify the cylinder, inside a set of 16 grey cylinders ordered from the lightest to the darkest grey, whose whiteness (or blackness) appeared the same as that of the coloured sample.

### Participants

Three psychology students, 2 females and 1 male, 21-24 years old, well trained in psychophysical research, with normal colour vision (checked with/by the Ishihara test). Two participant repeated the whole task five times and one participant six times on different days.

### Procedure

As in experiment 1, the cylinder-like coloured samples were put one at a time on the centre of the white floor of the light booth; a tray with 16 grey cylinders described in *materials* was also put in the viewing booth with the same illumination and the participant's task was to identify the cylinder in the tray showing the same whiteness (or blackness) as the coloured sample. The number of the cylinder, hidden to the participant, was recorded.

### Results

The white (or black) appearance of the achromatic colours in the series of the 16 greys was quite different from the white (or black) appearance of the test chromatic samples; nevertheless the task of comparing the whiteness (or blackness) of the achromatic colours with that of the chromatic ones resulted easier than expected.

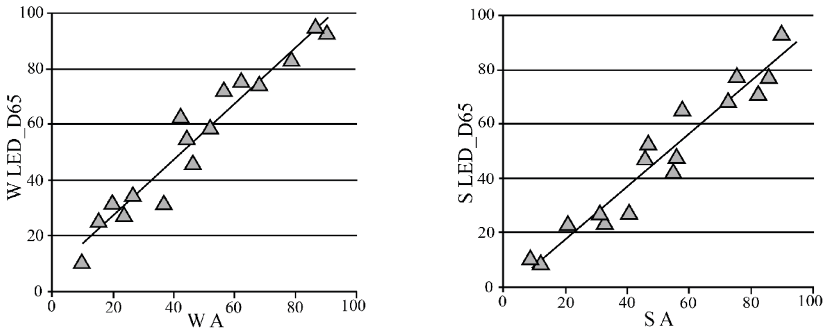


**Fig. 10.** Subjective evaluations of whiteness (W) and blackness (S) as a function of the A and LED illumination. The LED and A correlations both for W and S are high (r(15) = 0,97, p < .0001), but also significantly different (p < 0.005 in the case of W; p < 0.05 in the case of S).

In this experiment (Figure 10), as in the previous one (Figure 8), the assessment of the whitish (W) and blackish (S) appearance was slightly but significantly different under the two light sources ($t(15)= -3.523$, $p < .003$) when whiteness was evaluated, and $t(15)= 2.59$, $p < .02$ when blackness was evaluated).

Here again the similarity of the chromatic samples to both white and black amounted up to 100% (correlation between white and black evaluations: $r(14) = -.996$, $p < 8,25E-16$; there is a very small difference between the evaluations of whiteness and the complement to 100 of the evaluations of blackness:. $t(30)= 2.04$, $p < 0.87$; Figure 11), and therefore there was no agreement with the present NCS which implies a much lower correlation.

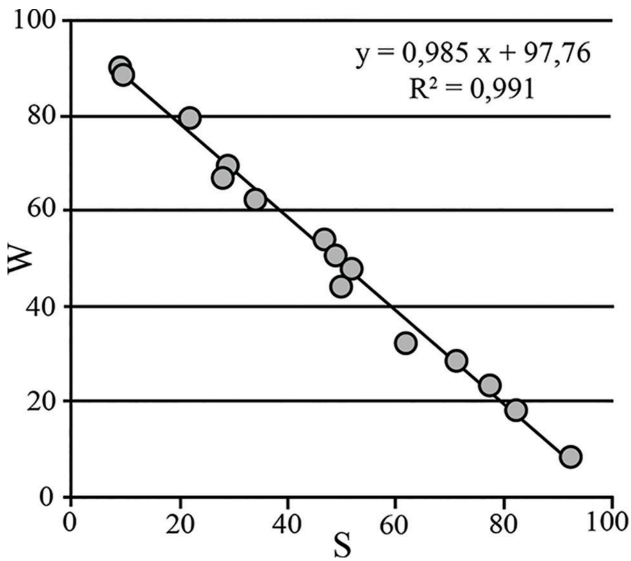


**Fig. 11.** Subjective evaluations of whiteness (W) as a function of subjective evaluations of blackness (S).

In this experiment the evaluation method was similar to the previous one as regards the task to be accomplished, that is to assess independently the whitish and blackish appearance of the 16 experimental colours, but there was a big difference in the instrument used to perform the assessment: not the slider which offered the possibility of choosing a spatial length to evaluate the similarity of colours to white and black, but a direct comparison of two whitish (or blackish) appearances one in the test colour and one in the achromatic cylinders, that is an asymmetrical colour matching. Replication of the previous unusual results is therefore remarkable.

### Test 3

In this experiment we used a coloured Mondrian as background, on the hypothesis that the concurrent presence of many chromatic colours could restore a viewing condition capable of giving results in agreement with the NCS.

### Participants

A group of 5 psychology students, 4 males and 1 female, 21-24 years old, with normal colours vision (cheeked with the Ishihara test), one expert in psychophysical research, and four students completely naive in vision research took part in the test.

### Procedure

The floor of the viewing booth was covered with a coloured Mondrian and in its middle a small white paper (7 x 7 cm) served as a local background for the 16 experimental samples.

The viewing conditions (A and LED_D65 illuminations) and the task were the same as in the first experiment, being the Mondrian background the only difference. The subjective evaluations were performed with the described slider.

### Results

Contrary to the previous experiments results showed no significant differences as a function of the two illuminations (in the case of questions about the whiteness under the LED illumination: $t(62)= 1{,}999$, $p< 0.136$; in the case of questions about the whiteness under the A illumination: $t(15) = -.680$, $p< .507$; Figure 12); on the other hand the W and S values were highly correlated ($r(30)= -0{,}905$, $p< 1{,}23E-12$) as before.

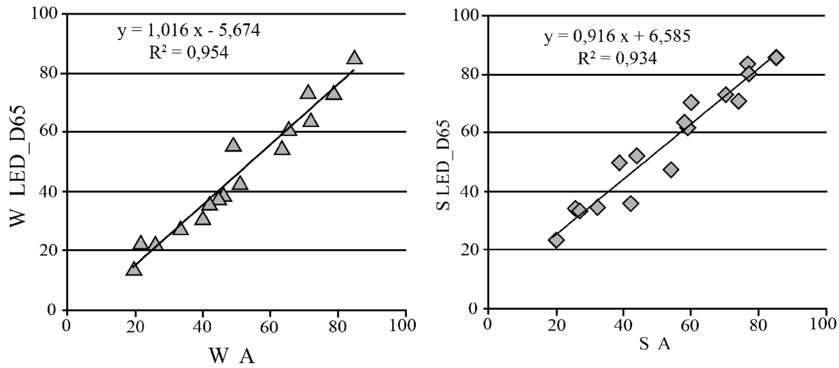


**Fig. 12.** Subjective evaluations of whiteness (W) and blackness (S) as a function of the two LED_D65 and A illumination.

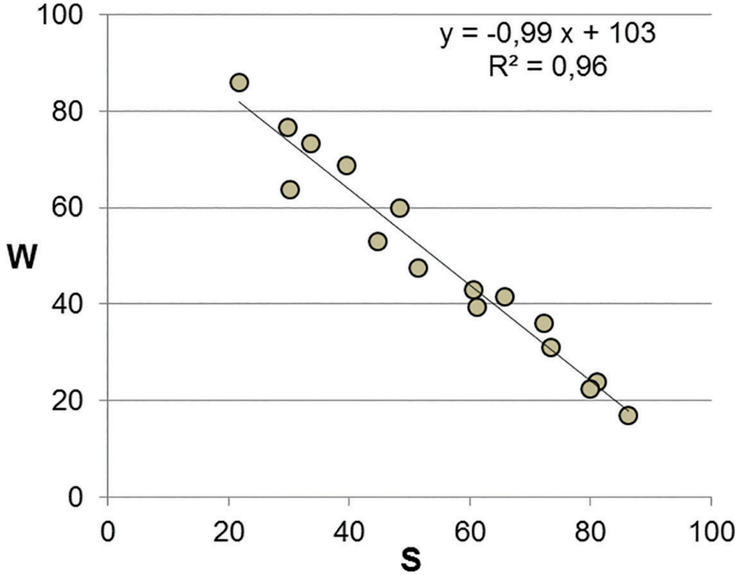


**Fig. 13.** Subjective evaluations of whiteness (W) as a function of subjective blackness (S).

Also in this experiment the overall subjective evaluations of whiteness and blackness summed up to 100% for all samples (Figure 13). This result implies the same problems as noticed before in regard to the structure of the present NCS, which seems to depend on the method used to assess the similarity of colours to the unique ones.

## Test 4

In this experiment a different method of investigation is tested, closer to the original method used by the founders of the current NCS.

### Participants

One female psychology student, 23 years old, with normal colour vision (checked with the Ishihara test) performed 5 times the task of evaluating the whiteness and the blackness of the 16 experimental colours.

### Procedure

The only difference with the previous experiments was the simultaneous presence in the viewing booth of four chromatic samples (out of the 16 studied ones), instead of one at a time. There were two conditions: 1) the four colours in the booth were of the same hue, thence of different nuances (chromatic, whitish, greyish, blackish); 2) the four colours were of the same nuance, thence of different hues (YR, RB, BG, GY). In both cases, when the task was to evaluate whiteness (or blackness), the four colours had to be *previously ordered* in a spatial series by the participant according to their subjective whiteness (or blackness).

The evaluations were done by means of the described slider and performed under the two A and LED_D65 illuminations.

### Results

Here we were interested in the relationship between W and S evaluations. Results from observations under light A (Figure 14) and those under light LED_D65 (Figure 15) were analysed and still found to be highly correlated and significantly different as before. In both 1) and 2) conditions results (Figure 16 *left*) were

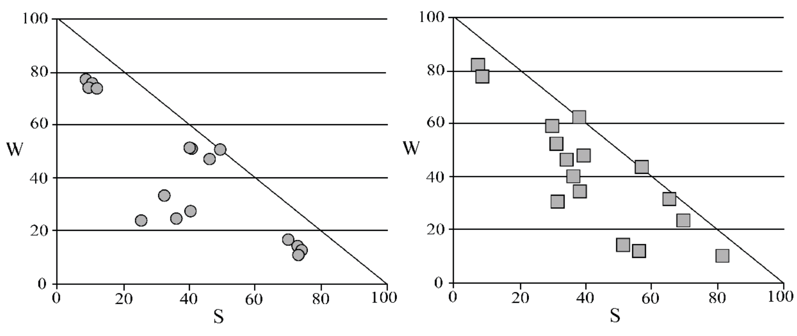


**Fig. 14.** *Viewing condition 1.* Subjective evaluations of whiteness (W) as a function of the subjective evaluations of blackness (S) under the two A (left) and LED_D65 (right) illuminations.

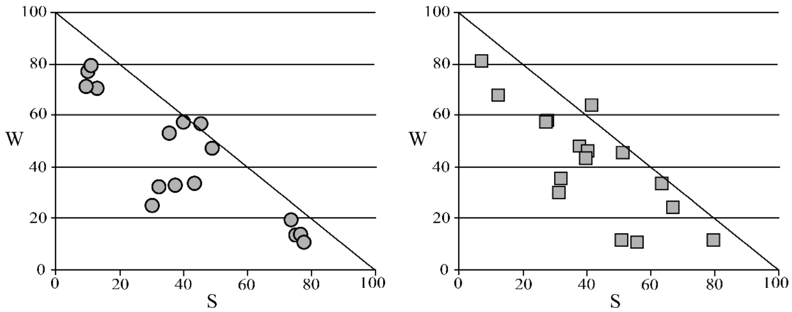


**Fig. 15.** *Viewing condition 2.* Subjective evaluations of whiteness (W) as a function of the subjective evaluations of blackness (S) under the two A (left) and LED_D65 (right) illuminations.

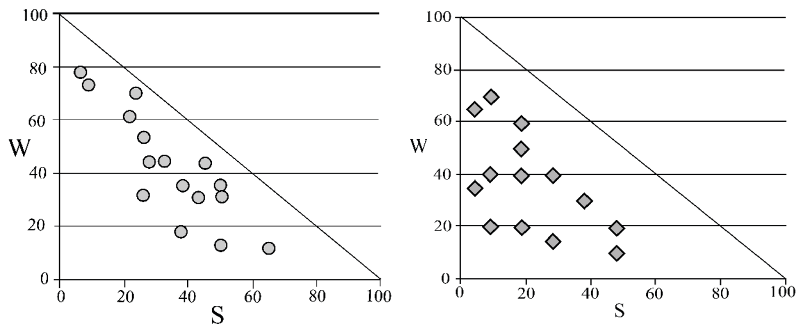


**Fig. 16.** Distribution of the resulted W as a function of S (*left*) in comparison with the current NCS W as a function of S (*right*). Almost all sums of whiteness and blackness evaluations are well below 100%.

different from the previous experiments, that is W and S evaluations did not sum up to 100% but showed a distribution similar to that of the actual NCS (Figure 16 *right*). Moreover the two conditions introduced no differences in the results ($t(63) = .349$, $p < .943$).

It seems that the novelty introduced into the procedure by showing a list of 4 samples inside the viewing box instead of only one spatially ordered from the least whitish on the left to the most whitish on the right substantially changed the results in comparison with those of the previous research. To verify whether this change really was due to that methodological variation another investigation was performed with a larger number of colour samples and participants.

## Test 5

This test was devised to verify whether the evaluations of whiteness (or blackness) of a colour inside a set of many other colours ordered in whiteness (or blackness) would agree with the structure of the actual NCS, as suggested by the previous experiment.

## Participants

Two female psychology students, 22 years old, with normal colour vision (checked by Ishihara test) volunteered in the experiment.

## Procedure

The experimental colours were 48 as described in *materials.* The 12 colours belonging to a hue quadrant were put in the centre of the viewing booth, and the participant's task was to order them from the least whitish on the left to the most whitish on the right (or from the least blackish on the left to the most blackish on the right).

Later the participant had to evaluate the similarity of each sample to white (or black) by using the slider. One participant performed the whole task 8 times, and the other 7 times, for a total of 15 evaluations for condition (48 colours, two illuminations, W and S evaluations).

## Results

As in the other tests evaluations differed depending on the illuminations. We are not dealing here with the details of this difference, which were anyway in agreement with the previous one: no difference derived from the two illuminations (t(95)= -.979, p< .427).

It seems that evaluations of similarity to one unique colour (either white or Black) agree with the actual NCS (Figure 17) when they are made inside an ordered

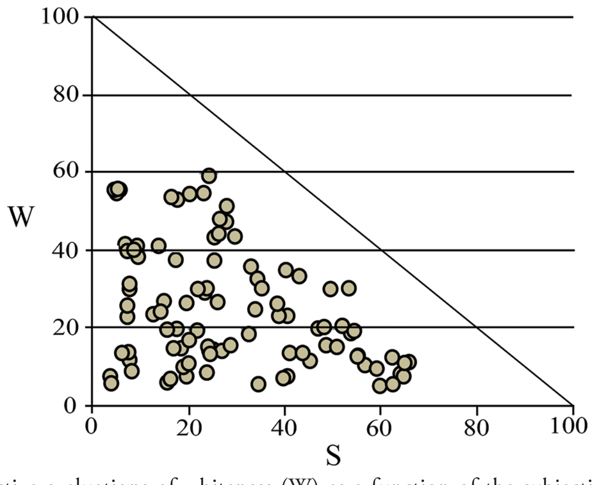


**Fig. 17.** Subjective evaluations of whiteness (W) as a function of the subjective evaluations of blackness (S) for all the 48 colours. All totals are well below 100%, in agreement with what happens in the current NCS.

sequence, that is when the observer has to find the suitable place for the test colour in the *bipolar scale* represented by the ordered samples. This means that the observer has two references for the evaluation, the left and the right side of the point where the evaluation is placed in the sample sequence, that is both similarities are determined at the same time, and one depends on the other summing up to 100% together ($r(95) = -.383$, $p < .0001$). This procedure is analogous to that followed by the authors of the current NCS, as described before.

### Test 6

This is a control test to compare results obtained with *chromatic* colours and those obtained with *achromatic* colours, that is with neutral greys.

If the results of the two conditions substantially agree we might conclude that evaluations of W and B in *chromatic* colours are focused on their grey appearance, independently of other aspects. This conclusion stresses that whiteness and blackness of a colour have nothing to do with the chromaticness of a colour, which should be evaluated independently, as suggested before.

### Participants

Ten psychology students, 4 males and 6 females, 21-25 years old, with normal colour vision (checked by Ishihara test) volunteered in the experiment.

### Procedure

In this experiment 16 grey samples, bent to appear cylindrical as described in *materials,* were put one at a time in random order in the viewing booth over a coloured Mondrian. Participants had to evaluate the W and S appearance of each sample by using the slider.

An analogous research with 19 grey samples and a mid-grey background was performed by Masin (1987), with which we compared our results. Table 4 shows the reflectance factor of the samples used by Masin, and the evaluation of their whiteness, blackness, and lightness emerged in his research.

Differently from our phenomenal way of studying colour perception, in the paper by Masin subjective evaluations are only plotted as a function of the reflectance factor, as is usual in psychophysics. Nevertheless in Figure 18 we have plotted his results according to our new way of presenting *subjective* data as a function of other *subjective* data. This way of plotting data allows us to discover that the blackness function of the two groups of greys in Figure 18 intersect at a point corresponding to the grey of the background. This division of greys into two groups seems to depend on the choice of a grey instead of our Mondrian background. This is the reason why we normally use either a white or a coloured Mondrian

**Table 4:** The table shows the reflectance factor, S, 100-W, and L* (CIELAB lightness) of each sample derived from the original graph by Masin.

| sample | reflectance factor | S | 100-W | L* [100-L] |
|---|---|---|---|---|
| 1 | 2,5 | 97,12 | 100,00 | |
| 2 | 5,0 | 97,12 | 100,00 | |
| 3 | 7,5 | 84,62 | 98,08 | 89,42 |
| 4 | 9,7 | 73,08 | 96,15 | 83,17 |
| 5 | 12,5 | 60,58 | 95,19 | 75,00 |
| 6 | 15,7 | 49,04 | 93,27 | 67,31 |
| 7 | 18,3 | 45,19 | 91,35 | 63,94 |
| 8 | 21,8 | 37,02 | 88,46 | 56,73 |
| 9 | 26,0 | 25,00 | 86,54 | 57,21 |
| 10 | 29,5 | 22,60 | 87,50 | 51,92 |
| 11 | 35,0 | 21,15 | 80,77 | 45,19 |
| 12 | 40,0 | 23,08 | 75,00 | 40,38 |
| 13 | 43,8 | 13,46 | 72,12 | 38,46 |
| 14 | 52,0 | 13,46 | 65,38 | 28,85 |
| 15 | 59,0 | 7,69 | 54,81 | 26,92 |
| 16 | 66,3 | 8,17 | 50,00 | 20,67 |
| 17 | 76,3 | 2,88 | 33,65 | 15,38 |
| 18 | 86,0 | 0,96 | 19,23 | 9,62 |
| 19 | 98,7 | 0,00 | 8,65 | 4,33 |

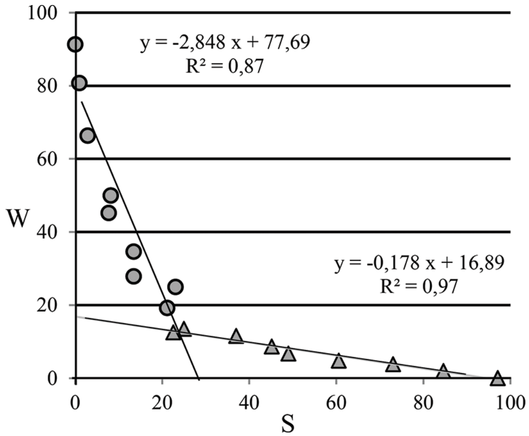


**Fig. 18.** From Masin (1987): the graph shows the subjective evaluations of whiteness as a function of the subjective evaluation of blackness. Circle: data belonging to a first group of colours; triangle: data belonging to another group of colours. The two regression lines intersect at the point corresponding to the background grey. Circles indicate the colours of a first group of greys (whiteness from 100 to 20), triangles indicate the colours of a second group of greys (blackness from 22,6 to 97).

background. In Masin's work the sums of whiteness and blackness decrease from 97 to 35 and then rise again from 40 to 91. From our previous results we expected that W and S appearance would always sum up to 100% because there are no chromatic appearance to account for.

## Results

Table 5 shows the white and black evaluations obtained in this experiment 6 under illumination A and LED_D65.

Our data are compared with those by Masin (1987) and shown in Figure 19. They are closer to Munsell Values than those by Masin, although slightly below them. The tight contiguity of our W and 100-S means that W+S is constant, as is expected to happen with achromatic colours.

The subjective evaluations of whiteness (W) and blackness (S), as given by Masin's observers and by the observers in this research are described in Figure 19 as a psychophysical function of the reflectance factor. In the current NCS W and

**Table 5:** The table shows the W (white) and S (black) evaluations with their SD (standard deviations) obtained in experiment 6 under illumination A and LED_D65.

| | ill. A | | | | ill. LED D65 | | | |
|---|---|---|---|---|---|---|---|---|
| samples | W | $SD_W$ | S | $SD_S$ | W | $SD_W$ | S | $SD_S$ |
| 1 | 99,7 | 1,0 | 5,3 | 2,7 | 99,3 | 1,3 | 4,9 | 2,3 |
| 2 | 95,0 | 5,0 | 7,3 | 3,7 | 97,0 | 4,0 | 7,8 | 4,3 |
| 3 | 84,5 | 12,0 | 15,4 | 8,3 | 90,3 | 6,0 | 9,2 | 4,7 |
| 4 | 82,0 | 13,7 | 19,7 | 8,3 | 79,5 | 14,0 | 17,8 | 5,3 |
| 5 | 65,9 | 20,0 | 33,7 | 11,3 | 73,3 | 15,0 | 25,5 | 12,0 |
| 6 | 49,5 | 17,7 | 43,3 | 12,3 | 60,7 | 19,0 | 34,4 | 15,3 |
| 7 | 56,8 | 13,3 | 42,3 | 14,0 | 59,8 | 20,0 | 41,0 | 18,3 |
| 8 | 41,9 | 22,0 | 48,3 | 12,0 | 54,2 | 19,3 | 47,7 | 20,3 |
| 9 | 31,5 | 13,0 | 67,4 | 11,7 | 42,7 | 11,3 | 57,2 | 11,0 |
| 10 | 30,7 | 9,7 | 62,0 | 14,0 | 46,1 | 21,7 | 60,8 | 14,0 |
| 11 | 23,5 | 11,0 | 73,5 | 11,0 | 30,3 | 10,7 | 64,8 | 13,0 |
| 12 | 17,0 | 9,0 | 84,3 | 7,0 | 22,3 | 8,0 | 74,8 | 12,7 |
| 13 | 9,5 | 4,0 | 90,5 | 4,0 | 15,6 | 4,7 | 86,7 | 8,3 |
| 14 | 7,3 | 4,0 | 94,8 | 3,3 | 11,2 | 3,0 | 88,2 | 9,0 |
| 15 | 6,5 | 2,3 | 96,5 | 2,7 | 6,2 | 1,7 | 95,6 | 6,3 |
| 16 | 4,2 | 1,0 | 99,6 | 0,7 | 4,7 | 1,0 | 99,1 | 1,3 |

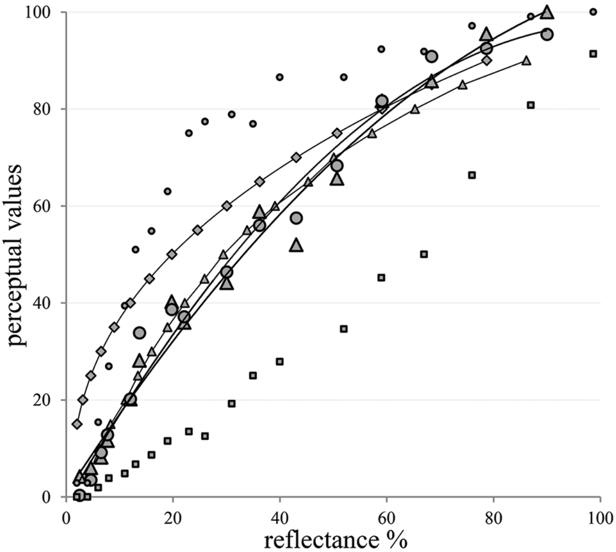


**Fig. 19.** The above graph shows the perceptual values of W and S as a function of the physical reflectance both in this experiment and in that of Masin (1987), the NCS Whiteness, and the Munsell Value. Small circles: Masin W; small squares: Masin 100-S; large circles: our W; large triangles: our 100-S; diamonds: Munsell Values (computed according to the Newhall et al. (1943) formula: $Y_{refl.fact.} = 1.2219\ V - 0.23111\ V^2 + 0.23951\ V^3 - 0.021009\ V^4 + 0.0008404\ V^5$); small triangles: NCS W.

Munsell Value are also depicted and appear very close. In the results of this test, either W or S, are very close to the present NCS W (or 100-S), confirming the accuracy of the evaluations produced by means of the slider. Evaluations of W and S from Masin's work (Figure 19) are quite extreme. The peculiar shape of the Masin curves seems due to his grey background (reflectance factor = 0,23 instead of our coloured Mondrian).

Contrary to the psychophysical tradition followed by Masin, we plotted (Figure 20) the *subjective* evaluations of whiteness as a function of the *subjective* evaluations of blackness (two phenomenal variables, a case of percept percept coupling by Epstein, 1982). As expected in the case of achromatic colours their sum is constant and equivalent to 100% (no-significant difference from 100, ($t(95) = -.797$, $p< .427$) in favour of the fact that there is no need of a place for the chromatic components. The sums of W and S in Masin are always very variable and rather lower than 100: this difference in respect to our results is probably due to the method used: magnitude estimation in his case, the slider without numbers in our research. We do not exclude that even the 3D shape of our samples may contribute to the differences in the results.

It is relevant to note that *no* determination of chromaticness is involved when the evaluation method is used in the same way as in our research. This means that

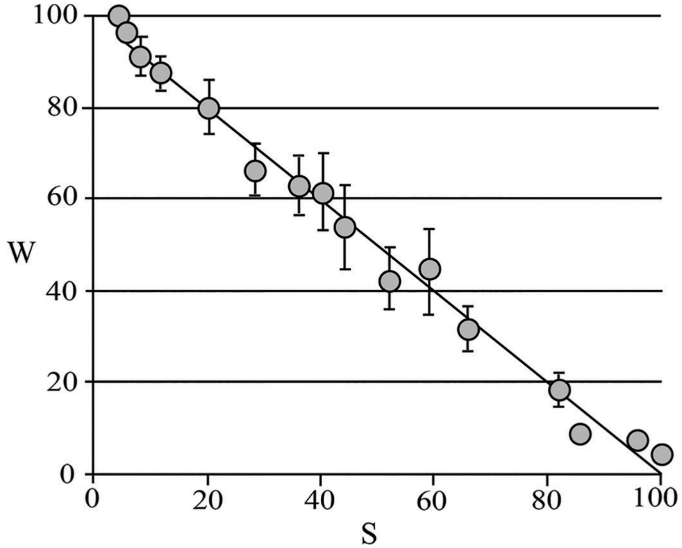


**Fig. 20.** Subjective evaluations of whiteness (W) are plotted as a function of subjective evaluations of blackness (S). Bars: standard errors.

evaluations of colour attributes operated according to our method are different from evaluations of colours performed according to the original NCS method, although they might appear substantially the same. The common task is to assess the similarity of a colour to one unique hue, i.e. how much a colour appears reddish, or whitish, or blackish, and so on; but this generic task can be performed in different methodologies, independent evaluations vs one dependent on the others, and these determine the kind of results which can be obtained. We suggest a new methodological development which will include three steps characterised by three bipolar scales: W-S; Y-R / R-B / B-G / G-Y; Gr-C (chromaticness, i.e. grey – maximum chromatic colour). The first step (W-S) has been achieved in this study; the second step (determination of the hue) has been realized by Hard et al. (1996); the third step should be concretized in a new research.

## Discussion

This article cites different studies carried out with different purposes having in common the fundamental question of the distinction between mixed colours and elementary colours and the consequent difficulty of evaluating the similarity of mixed colours to the elementary ones. This characteristic is specific to the natural system (unlike the Munsell system in which the differences rather than the similarities between colours are highlighted) even if the general statement of the principle does not include the definition of the methodologies to be followed: the use of bipolar scales for the definition of the hue and of 'tripolar' scales (triangles) for the definition of the nuance is not an essential characteristic of the natural colour system, but a simple and effective methodology conceived and successfully practiced by the authors of the current NCS system. We have found that it is not the only possible methodology, and that a different colour evaluation methodology requires a review of many other aspects of the system. Most likely the final result will not be very different from the current one, but this will only be known in hindsight.

In many researches we try to detect what changes in the perception of colours as a consequence of specific changes in some environmental variable, for example in the surround (light, dimensions, 3D, etc.) or in the subject itself (attention, adaptation, etc.) . Having discovered almost by chance the peculiar relationship between the apparent whiteness and blackness of a colour according to which the two aspects are often complementary, that is, they add up to a constant generally 100%, we have on the one hand recovered research already carried out for other purposes but in which there were quantitative colour description procedures that could be analysed from our point of view; and in addition we have carried out other quantitative descriptions with various methodologies to confirm or challenge our hypothesis. The need to carry out the evaluations with very expert people, to avoid the intrusion of unexpected preconceptions, imposed the adoption of a few participants, each of whom made many observations, as Metelli et al. (1985) had already explained at the time in a much cited research. We have thus arrived at the specification of the essential elements which lead to a description of the achromatic aspect of colours in terms of complementary whiteness-blackness, i.e. describable in a bipolar black-white scale, as supported by Hering.

## Conclusion

Our results confirm that the constant sum of W and S at 100% in tests 1, 2, 3, and 6 really refers only to the achromatic components, while the chromatic aspects of colours have to be described independently from these. On the other hand a different procedure used in experiment 4 and 5 gives results compatible with the actual NCS. The difference between our results and the actual NCS characteristics seem due to the method used here to evaluate W and S, that is, evaluation of one attribute at a time (unipolar scaling, often used in practice) vs locating the colour inside a bipolar or tripolar (triangle) scale. Our method highlights the bipolarity of the W-S aspect, which was only assumed by Hård et al. in a preliminary study in the light of Hering (1920) theory.

Another relevant difference is the shape of the coloured samples, which in other research is flat while in our is cylinder -like i.e. curved The structure of the resulting colour system therefore is heavily affected by the *method* used. The relevance of the method in determining the results has already been highlighted by Bosten & Mollon (2012) in a different research field.

Another alternative methodology to determine the similarity of a colour to the six elementary ones is to locate position the colour sample inside a double cone with a vertical line showing the White-Black axis and four cardinal axes in the equator to show the place of the four maximally chromatic elementary hues. One would need only one trial to determine all the relevant similarities with the unique colours, but the procedure seems to involve quite large variability. Only a specific research along this direction can show the utility of this procedure.

## Abstract

This phenomenological research investigates how it is possible to determine the extent to which a chromatic colour appears white and black in order to use it to build a new Colour Rendering Index. We tested two methods of subjective evaluation; in the first, the perceptual presence of white (and black) in a colour alone was assessed on a unipolar intensity scale, independently for the two attributes. In the second method, evaluations of whiteness (and blackness) were conducted for colours presented in a sequence ordered from the least to the greatest presence of the respective attribute. In both tests evaluations were made either by moving an arrow on a slider from left (minimum) to right (maximum) or by choosing a grey cylinder that matched the same degree of similarity to white (and black) as the test colour. In four experiments, 16 colours of 4 hues and 4 different shades were studied; in a fifth experiment, 48 colours, 12 for each quadrant of the colour wheel, were studied; finally, in another test, 10 greys were studied. In the first three experiments, the results were unexpected, as the evaluations of whiteness and blackness were complementary, adding up to 100%, while in the current NCS, 100% includes not only the evaluation of white and black but also that of chromaticness, therefore white and black are not complementary. In the fourth and fifth experiments, the sum of the evaluations of white and black was always less than 100%, in accordance with the present NCS. In the last experiment, the evaluations of white and black given independently to the 10 greys samples were complementary, confirming the bipolar nature of white-black continuum. Suggestions have been provided to resolve the discrepancy between the results of this research and the structure of the current NCS.
**Keywords:** white, black, bipolar scale, NCS, CRI

## Zusammenfassung

Diese phänomenologische Forschung untersucht, wie es möglich ist, den Umfang zu bestimmen, in dem eine chromatische Farbe als weiß und schwarz erscheint, mit dem Ziel, einen neuen Farbwiedergabeindex zu erstellen. Wir haben zwei Methoden der subjektiven Bewertung getestet. In der ersten wurde die wahrgenommene Präsenz von Weiß (und Schwarz) in einer Farbe allein auf einer unipolaren Intensitätsskala unabhängig für die beiden Attribute bewertet. In der zweiten Methode wurden Bewertungen von Weiß (und Schwarz) für Farben durchgeführt, die in einer Reihenfolge präsentiert wurden,

die von der geringsten bis zur größten Präsenz des jeweiligen Attributs geordnet war. In beiden Tests wurden Bewertungen entweder durch Verschieben eines Pfeils auf einem Schieberegler von links (Minimum) nach rechts (Maximum) vorgenommen oder durch Auswahl eines grauen Zylinders, der den gleichen Grad an Ähnlichkeit zu Weiß (und Schwarz) wie die Testfarbe aufwies. In vier Tests wurden 16 Farben mit 4 Farbtönen und 4 verschiedenen Schattierungen untersucht. In einem fünften Testt wurden 48 Farben, 12 für jedes Quadranten des Farbkreises, untersucht. Schließlich wurden in einem anderen Test 10 Grautöne untersucht. In den ersten drei Tests waren die Ergebnisse unerwartet, da die Bewertungen von Weiß und Schwarz komplementär waren und sich zu 100% addierten. In den aktuellen NCS bezieht sich 100% jedoch nicht nur auf die Bewertung von Weiß und Schwarz, sondern auch auf die von Chromatizität. Daher sind Weiß und Schwarz nicht komplementär. In den vierten und fünften Test war die Summe der Bewertungen von Weiß und Schwarz immer weniger als 100%, im Einklang mit dem aktuellen NCS. Im letzten Experiment waren die Bewertungen von Weiß und Schwarz, die unabhängig für die 10 Grautöne abgegeben wurden, komplementär, was die bipolare Natur des Weiß-Schwarz-Kontinuums bestätigt. Es wurden Vorschläge gemacht, um die Diskrepanz zwischen den Ergebnissen dieser Forschung und der Struktur des aktuellen NCS zu lösen.

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