House Painting with NCS in the USA

Giordano Beretta
Computer Peripherals Laboratory
HP Laboratories Palo Alto
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We explore the use of the Natural Color System for designing color schemes in exterior and interior design. The availability of paints in the US market to realize such a color scheme is researched. Finally, we examine the performance of paint matching systems for one particular paint.

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1.0 Introduction

We recently had to repaint our house. Like many traditional houses, also ours was painted in a single off-white color inside-out. We asked several color scientists how they designed a color scheme for their house or apartment the last time they had to paint. We were surprised to invariably receive the same answer: “I did not want to take any risk; I painted everything white.” This prompted us to a challenge and try to design a bold color scheme.

Based on previous work, we decided to design the color scheme as a set of symmetries in a perceptually defined color space. Although we had the software tools for designing a scheme in CIELAB, it turned out that using a computer was inconvenient and it was difficult to reliably predict in an uncontrolled environment the color appearance for small color nuances. The color chips available from paint stores were not suitable because the colors were not ordered in three dimensions.

Since the second edition of the Natural Color System (NCS) atlas had recently become available and is widely used by designers in some European countries, we decided to design our color scheme using this system. Contrary to some other countries, here in the USA paint manufacturers do not use NCS to specify colors. Although most paint stores can “computer match” any color, this was not a viable solution in our case.

The interior decoration of our house has a strong Japanese trait. One of the cornerstones in Japanese architecture is that color is not used to create varied light, but to intensify the natural effect of light. Thus we had to pay special attention to the spectral reflectance curves of paints. This limited us to the use of pre-mixed paints, avoiding computer matches based on metamerism.

In this paper we report on how we designed the color scheme, how we selected a paint brand, and how close we were able to match the colors in the NCS scheme with actual premixed paints available in the USA. For one of the colors in the scheme we also analyze how close a computer match is to a reference color in the real world of a paint store.[1]

2.0 Color schemes and color spaces

2.1 Color in architecture

In the past, the colors used to paint houses depended on the locally available pigments and their cost [5]. Today thousands of colors are available; many paint stores are equipped with colorimeters and ink formulation software that allow them to match any color within

1. The slides are available at http://www.hpl.hp.com/personal/Giordano_Beretta/Acrobat/Reports/iscc2Slides.pdf and a set of photographs can be found in the directory http://www.hpl.hp.com/personal/Giordano_Beretta/Bildli/PCD4004/

a manufacturer's gamut. This large choice makes it much harder to decide on a color scheme for a house.

To help home owners in their decision process, most paint manufacturers compile standard color schemes among which people can choose the scheme they like best. However, especially in Europe there is a trend against strict methodologies and the systemization of color schemes for buildings [14], probably because the abstract choice of a scheme ignores the context in which the building is situated. This prompted us to ignore the standard color schemes provided by manufacturers.

Most of the time architectural color is functional, as opposed to reference colors, which refer to natural objects. Although functional color can be arbitrary, it cannot be random, as random colors tend to clash and lead to coloristic garbage. To be æsthetically pleasing, the colors in a scheme must be tied together by a fundamental principle.

In earlier work related to the creation of business graphics [2], we noted how pleasing color schemes can be designed by selecting colors so that they form symmetries in perceptually uniform color spaces. Several authors, such as Nemcsics [13], Spillman [17], Tonnquist [18], Sivik and Hård [16], Tosca [19], and Prieto [14], have written about the positive qualities of designing architectural color schemes following rules in a perceptually defined color space.

Authors like Sivik and Hård [16] have expressed strong opinions against notions like harmony and complementarity. From a semiotical point of view [3], in these papers the authors have looked at color mostly from a syntactical point of view, when color is purely concrete.[2] In our case we are concerned with a specific architectural application and our considerations are about semantic, i.e., urbanistic and structural, functions of color. We hope this distinction will spare us from Sivik and Hård's criticism.

2.2 Selecting colors in CIELAB

In our earlier work [2], we had chosen CIELAB as the perceptually defined color space. The main reasons were:

1. it is based on CIE colorimetry
2. it is perceptually uniform with relatively good perceptual correlates
3. it is straightforward to implement in computer programs

The tool we had developed was computer screen based, and allowed graphic designers to interactively develop a color palette for use in desktop publishing. Architectural color can be simulated on a computer screen, but in practice this is useful only to give a very rough idea in a sketch. Color appearance models are available to map the color reproduction on the screen so it appears the same as when viewed under an arbitrary illuminant, but this is

2. In Max Bill's sense of color that exists by itself without any iconic relation to an object.

cumbersome. Finally, a computer screen is tiny in comparison to a building, so it is impossible to judge the size effect, the interaction with the ambient, and the total appearance.

In summary, while CIELAB is a very good color space for computer applications, an interactive software tool based on CIELAB is not a good choice for practical color selection in architecture.

2.3 Selecting colors with paint chips

Consumers can bring items such as fabric to the paint store and appreciate the combinations with paint chips (color swatches) under controlled illumination, or they can take chips home and appreciate them in situ when the color scheme can be designed from a clean sheet. The colors in a collection are often selected by professional color consultants, trend forecasters, and color stylists. The chips are arranged on strips of bristol or index grade paper and have words like “system” or “calibrated” in them.

Paint stores offer large free collections of these paint chip strips. Most manufacturers order the strips loosely by hue and saturation. The problem with the paint chips is that the colors on each of them are often ordered in small groups of similar pigment formulation. Such an arrangement is not perceptual and there is no order nor scale. This makes it difficult to change a color in just one perceptual dimension; while a coarse color selection can be performed, it is hard to find a perceptually close color.

Furthermore, the imaginative color naming schemes popular with paint manufacturers are not helpful to describe the relation among colors in a palette — how do *Monet Moonrise* and *Dusty Mink* interact? Why is a given color called *Monet Moonrise* by one manufacturer and *Mesa Sunrise* by another manufacturer? To successfully develop a scheme, we need a system that allows us to express the perceived relation among colors.

2.4 The natural color system NCS

The NCS natural color system [7] is a Hering-type color opponent system. Because it has the concept of color nuances — colors of the same whiteness and blackness but different hue — it is believed to be more suitable for designing color schemes for architectural uses [8, 17]. In several of the references in this paper, colors are specified in NCS.

The Scandinavian Color Institute publishes an NCS color atlas that is produced to strict colorimetric tolerances. This atlas can be used in a light booth to select colors, on location to appreciate a color in context, and to match an existing color visually. If the atlas cannot be afforded, the Scandinavian Color Institute also sells an inexpensive color index, which is what we used, because the second edition atlas was not yet available when we realized our paint project. Ronnier Luo’s LLAB color appearance model allows the prediction of color in NCS notation from colorimetry.

NCS is a Hering-type color space based on the three opponent color pairs black-white, red-green and blue-yellow. Within a hue, the colors are ordered by their white and black contents, from which saturation can easily be calculated. These three pairs form the axes for the three-dimensional NCS color solid, whose geometry is a double cone.

In practice, a pair of two-dimensional representations (projections) is used: the NCS color circle and the NCS color triangle. The hue circle is defined by the red-green and blue-yellow axes. Each quadrant is partitioned in 10 slices of equal angle, as shown in Figure 1. The 400 indicated hues determine the *NCS hue* Φ.

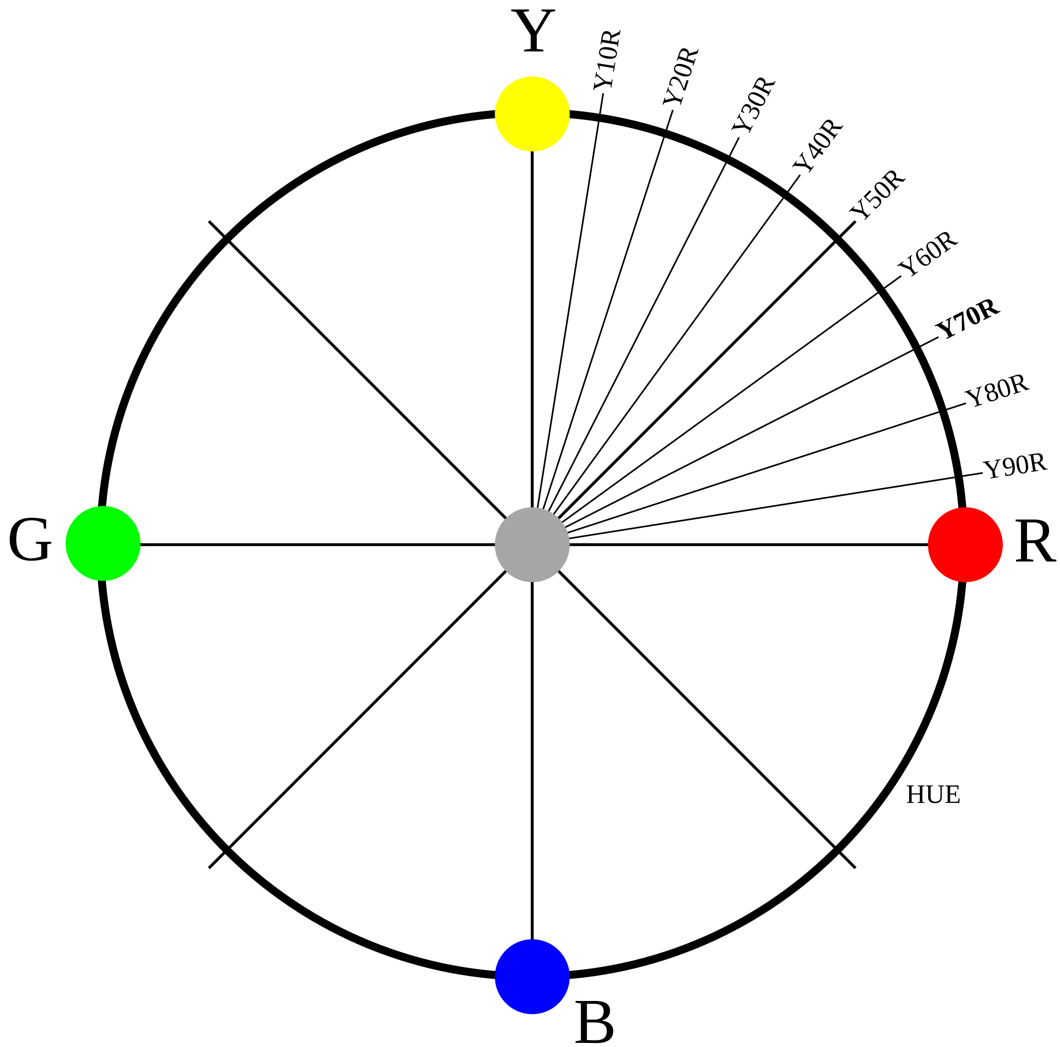

FIGURE 1. The NCS color circle is a horizontal cut through the middle of the NCS color solid, where the four elementary colors are placed as the four cardinal points. Every quadrant between two elementary colors is divided into 100 steps. In this color circle, the hue Y70R is read as *yellow with 70% redness*.

Colors are described as relative amounts of the elementary colors so that the sum of the attributes is 100 [7]. Hence, units are percentages, unrelated to colorimetric quantities and unrelated to pigment mixtures. The hue notation consists of two letters which designate a quadrant and a number which indicates the relation between them in percent. The hue Y32R is yellow with 32% redness and 68% yellowness, while Y70R is a red hue with 70% redness and 30% yellowness.

The NCS color triangle is a vertical cut through the NCS color solid at each hue, as shown in Figure 2. On the left side of the triangle is the gray scale from white (W) to black (S) and at the right of the triangle is the maximum chromatic color (C) of the hue. The color triangle enables the *nuance* of the color to be indicated, i.e., its degree of resemblance to the elementary colors white and black and to the full chromatic color of the same hue.

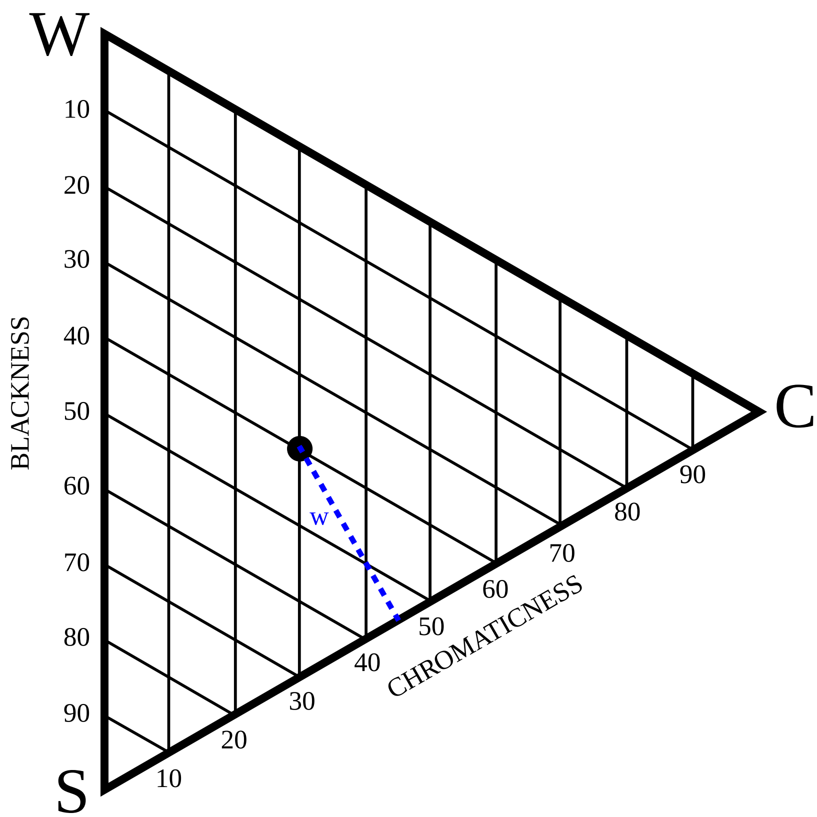

FIGURE 2. The NCS color triangle is a vertical cut through the color solid at each hue. At the left side of the triangle is the gray scale from white (W) to black (S) and at the right of the triangle is the maximum chromatic color (C) of the hue considered. The black dot indicates a nuance with a blackness of 40 and a chromaticness of 30. The dotted line indicates the whiteness *w* = 30.

The scale on the vertical edge in Figure 2 indicates the *NCS blackness s*, and the scale on the lower edge indicates *NCS chromaticness c* (defined as the sum of the chromatic attributes). *NCS whiteness w* is the distance of a nuance from the edge SC of black colors. The sum of the values of the attributes is always 100, hence the whiteness must not be noted [7].

Also here, the scales for whiteness, blackness, and chromaticness are divided in 100 parts, so the numbers can be interpreted as percentages. The *nuance notation* indicates first the blackness with two digits and then the chromaticness with two digits. The nuance notation

4030 thus indicates a color with a blackness of 40 and a chromaticness of 30. The whiteness of this nuance is 100 – 40 – 30 = 30.

The nuance and hue notation together give the complete *NCS notation*. In this notation S 4030–Y70R, S stands for Second Edition, 4030 stands for the nuance, i.e., the degree of resemblance with black S (40% blackness *s*) and the maximum chromaticness *C* (30% chromaticness *c*). Finally, –Y70R stands for the hue.

The NCS chromaticness is intermediate between CIE 1976 chroma and CIE 1976 saturation [8]. The *NCS saturation* is defined as [7]

$$m = \frac{c}{c + w} \quad \text{or} \quad m = \frac{c}{100 - s} \qquad \text{(EQ 1)}$$

The atlas indicates also the *NCS lightness* (ν) and the photometric luminous reflectance factor (Y_l), which are not used in this paper. The atlas contains a total of 1750 color samples; a table at the end contains the NCS notations for the primary NCS standards after measurements.

As an opponent hue system, NCS is not perceptually uniform; for example, the hue circle is not equi-spaced [18]. Therefore, for evaluating color differences we must convert the colors to the CIELAB color space, where we can use the CIE94 formula [4]

$$\Delta E^*_{94} = \sqrt{\left(\frac{\Delta L^*}{k_L \cdot S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C \cdot S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H \cdot S_H}\right)^2} \qquad \text{(EQ 2)}$$

with

$$\begin{aligned} S_L &= 1 \\ S_C &= 1 + 0.045 \cdot C^*_{ab} \\ S_H &= 1 + 0.015 \cdot C^*_{ab} \end{aligned} \qquad \text{(EQ 3)}$$

and

$$k_L = k_C = k_H = 1 \qquad \text{(EQ 4)}$$

The computation of the lightness and chroma differences is straightforward. We compute the hue difference with the formula proposed by Sève [15]

$$\Delta H^*_{ab}{}^2 = 4C^*_1 C^*_2 \left(\sin\frac{\Delta h^\circ}{2}\right)^2 \qquad \text{(EQ 5)}$$

2.5 Selecting colors with NCS

Sivik and Hård [16] have explained in detail how to design color schemes with the NCS system. With the atlas it is very easy to determine the locus of colors with a constant attribute as described by Hård [7]; this is illustrated in Figures 3–8.

In Figure 3 the invariant is the whiteness (as indicated in Figure 2, the whiteness is the distance of a nuance from the chromaticness scale edge). The locus of points in such a scheme is a straight line parallel to the edge *SC*. The colors on the edge *SC* itself are called *deep*. Figure 4 shows the case in which the invariant is blackness. The loci in this case are straight lines parallel to the edge *WC*. The colors on the edge *WC* are called *bright*.

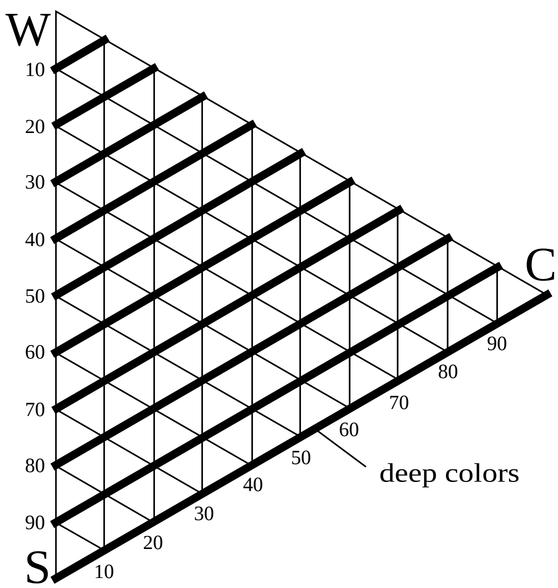

FIGURE 3. Color samples with the same NCS whiteness *w*.

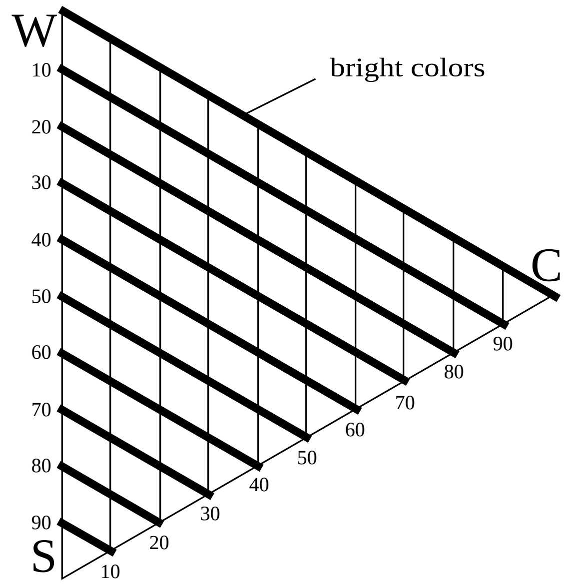

FIGURE 4. Color samples with the same NCS blackness *s*.

This ability to form different color combinations based on whiteness and blackness is one of the strong points for architects and designers in the NCS system.

Figure 5 illustrates that color samples which have the same chromaticness *c* are found on a line segment parallel to the gray edge *WS*. Figure 6 indicates that color samples having the same nuance are found in the same position in the color triangle, regardless of hue. The nuance is specified with the four digits comprising the blackness and the chromaticness, in our example 2030.

The last two invariants for designing color scales in NCS are less common, at least in the literature. Figure 7 shows that color samples which have the same saturation are found on a straight line through the black point *S*. Note that contrary to the other attributes, which are percentages, the NCS saturation is a fraction. This is also the case for the NCS lightness. Figure 8 shows how in the atlas color samples having the same lightness are found on a straight line, the location of which depends on the NCS hue Φ.

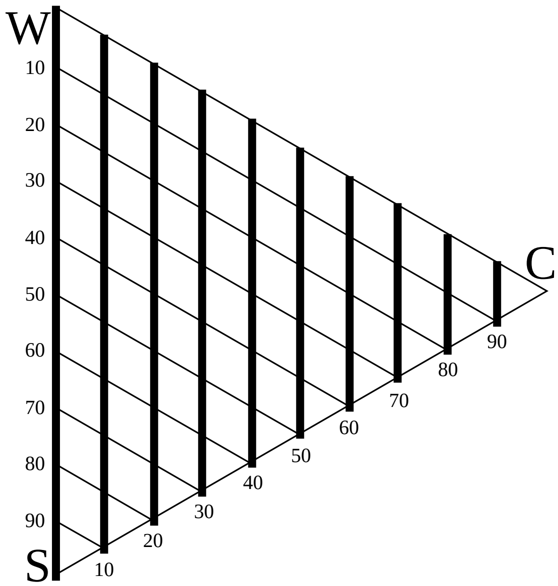

FIGURE 5. Color samples with the same NCS chromaticness *c*.

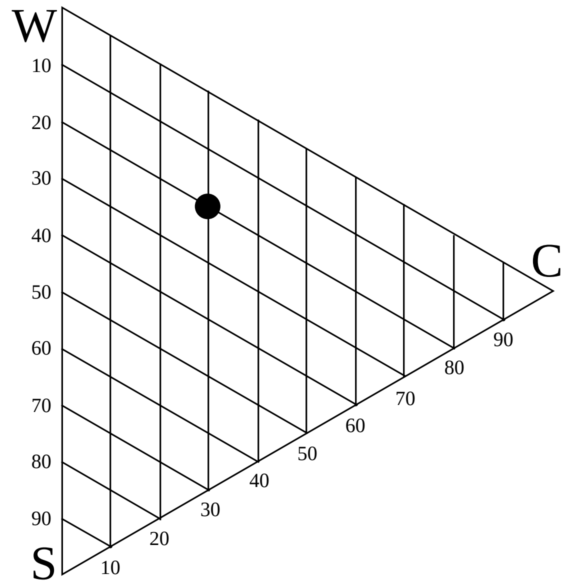

FIGURE 6. Color samples with the same NCS nuance 2030 (regardless of hue).

The *NCS atlas 96* has a page with the hue circle, a page with the neutrals and off-whites (c = 00 and c = 02), and all pages with the hue leaves in steps of ten units; finally there is a table with the colorimetrically precise NCS-notations. The *NCS index* is divided into four groups, one for each hue quadrant. In each groups there is an index page for each nuance. The various hues in the quadrant are always on the same location on the index page.

In our project the priority was for the semantics of the color scheme. Therefore, we did not use Figures 3–8 to build a color scheme, because that would only by syntactic. Instead, we used the invariants as starting points from which we could change the color for a certain function by changing only one attribute at a time. We used the NCS atlas for guidance, not as a rigid set of principles or rules. The atlas allowed us to limit the total attributes in the color scheme, by identifying hues and nuances, although in practice we had to compromise on the available paints.

3.0 Architectural principles for a color scheme

3.1 Exterior

When a dwelling is painted, often two different color schemes are used. The first scheme is designed by the architect and applies to the façade, trim, and doors. The second scheme is compiled by an interior designer or decorator for the paints to be used inside the dwelling. In the project described in this paper, we were able to design a single color scheme for both exterior and interior.

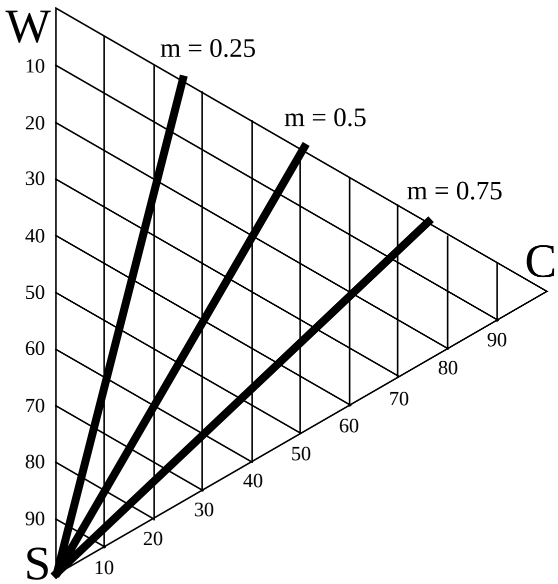

FIGURE 7. Color samples with the same NCS saturation *m*. Colors on such a line are called a *shadow-series*.

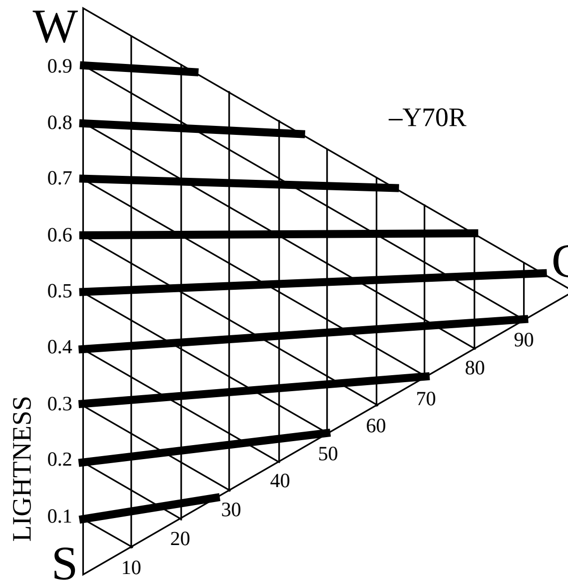

FIGURE 8. Color samples of hue Y70R with the same NCS lightness ν. Note the ordinate here indicates the lightness ν.

In architectural color design, not only are the interrelations among color elements important, but more fundamentally the exterior relations to building surroundings (contextual aspect) and building structure (structural aspect) [17]. To harmonize with the existing neighboring houses, the design started with the selection of a color for the façade.

3.1.1 Urban context

The house is located in an area of a suburban town that at development time was at the town’s periphery, where apricot orchards gave way to marshland. It is part of a subdivision created shortly after World War II to provide inexpensive housing to young families formed by soldiers who had returned from the war and were at the beginning of their civilian career. The modest lots and houses are relatively small and have a very simple floor plan. Our house consists of two parallelepipeds with a square base: one for the living space and one for the garage.

With the creation of the Silicon Valley, the town grew, engulfing and extending beyond the subdivision. More recently, in the roaring period of quick economic wealth of the 90s, the area between the city center and this peripheral area has undergone quite dramatic changes. Block after block properties have changed hands and the new owners have replaced the old houses with large volumes that Tosca labels “modern mish-mash buildings” [19].

Our goal was to build a semiotic bridge between our modest ranch style house and the new swanky residences. This suburban city is embedded in a lush artificial landscape known as “urban forest,” consisting of streets lined by tall trees[3] and properties with numerous trees and shrubs. Under this dense canopy and green environment, many houses are painted in earth colors.

3.1.2 Façade color

Driven by this contextual consideration and the temptation to make a semiotic allusion, we decided to choose an earth color for the façade. Due to the difficulty to judge the effect of a color from a small patch in a color atlas, we walked the neighborhood streets until we found a house with a color we liked. This color was burnt umber[4], a red-brown color from iron and manganese compounds that traditionally depended on the fact that iron oxide had been formed during the burning.

Our house is on a street lined with mature camphors; the property line in the back is marked with tall redwoods (Sequoia sempervirens). The house on the left from the street is painted in a vivid light blue. This combination of surrounding colors prompted us to opt for a post-modern color that is just on the outer chromaticness border in the locus of burnt umbers [5].

We measured the façade’s color by placing samples from the NCS color index directly on the surface, as described by Fridell Anter for measuring inherent color [6]. On a sunny March day at 10 am we used two observers with normal color vision, as described in op. cit. The NCS specification for this color is S 4010–Y70R; for illuminant D_{65} and the 10˚ standard observer the CIELAB coordinates are ($L*$, $C*$, h) = (60, 12, 50).

Color is only one aspect of appearance. The façades of the new swanky houses are typically finished in a high granularity stucco. This texture of the surface modulates the light depending on the sun position, generally darkening the appearance.

By contrast, the façade in our ranch style house is covered with the characteristic wood siding, which is a smooth surface. This put us in a difficult quandary. We could “compensate” for the stucco’s granularity by increasing the blackness in the color specification. However, the house is situated in a hot meridional[5] climate and has no insulation in the walls, so we wanted to keep the color as light as possible.

With two tall redwoods in the back; several mature privets (Ligustrum lucidum), camellias (Camellia japonica), and various Rhododendra around the house, there is always some shade on the walls. We thought that if we chose a paint that has a spectrum with inflec-

3. According to the City’s Comprehensive Plan, Goal N–3, the urban forest consists mostly of southern magnolia, American sweetgum, London plane, Modesto ash, camphor, Chinese elm, and holly oak.
4. Umbers are brown, beige, and grey-pink colors of low chromaticness.
5. Approximately 37˚25’N.

tions, illuminating changing spectral composition from the vegetation and the sun's path would provide sufficient color modulation to compensate for the flat wall surfaces.

3.1.3 Structural detail

Architecture is the creative work with volume to design space for living purpose. Colors have a spacial effect; warm colors tend to bring objects nearer, while cold colors appear to remove objects; lightness contrast makes this effect more pronounced [13, Section 5.1.1]. This means that the colors in a façade have to be chosen carefully because they interact, a fact already described systematically by Leonardo da Vinci.

Nemcsics discusses in detail how to select the colors for structural detail depending on context and structure. The new houses we used for inspiration have more or less elaborate features in their façades, such as gutter, cornice, course, casement, sash, and footing. The most architecturally prominent detail is the course. Since the course can be extensive, in the new houses a neutral color such as black or a light gray is often chosen. This concords with Tosca's observation that wealthy people tend to select schemes with few dark and muted colors [19].

In our modest ranch house these features are mostly missing, which confers the construction a boxy look. This appearance is countered by a relatively tall fascia under the Dutch gutter. In the "living space box," this fascia and the casements are the only features. The "garage box" has more features; when a room was added on top, the overall architectonic balance was broken, and architect Tony A. Carrasco added some features to break the tall box into two stacked flat boxes. On the side forming a concave angle with the main part the architect added a conspicuous pergola (trellis) continuing the fascia, while in the front he added a redundant gutter optically continuing the fascia. On the third side he added a stair with a conspicuous bannister. With this measure the tall box was broken into two stacked flat boxes, maintaining the ranch style look of the house.

Because of this modest nature of the features, we decided to add bold colors to our color schemes. For the trim (fascia, casement, sash, bannister, and pergola) we decided for a hue diametrically opposed to the façade color, i.e., B70G. We would have preferred a 0505 off-white nuance, but it is not available in the NCS atlas for this hue. Our selection therefore fell on S 0510–B70G. This increased chromaticness intensified the overall post-modern character of the color scheme.

For the main door we decided to select a hue half-way between façade and trim: R20B. This hue is 10% more reddish than pure symmetry would dictate. To avoid too garish an appearance, we decided to select the hue one page towards the façade color (like a typographic ligature), since it occupies a larger surface (the door is in framed with a casement of trim color).

For the door nuance we decided for the same chromaticness as the dominant interior walls, namely 50 (see below). This invariant prepares the visitor at the threshold for the chromatic atmosphere inside. For the blackness, we decided for a deep color, matching the exterior wall in which the door is set. The full color specification for the main door is thus S 4050–R20B, i.e., the same blackness as the exterior wall, the same chromaticness as the interior wall, a hue at balance between the exterior wall and trim.

3.2 Interior colors

In the previous section we have seen how the color scheme for the exterior was chosen strictly in function of the urban context of the house. For the interior such a constraint is no longer necessary; however, the interior colors were not chosen in a new scheme, rather the scheme of exterior colors was extended inside the house, as mentioned in the case of the door color.

As a guideline to understand how to extend the scheme from the exterior to the interior, it is necessary to understand the two author's cultural baggage. Since city colors are experienced predominantly from the streets rather that the interior of residences, we first explore the memory images ingrained in the author's visual system. This discussion will allow the reader to understand how we were able to extend the exterior color scheme to the interior.

Lenclos, who has systematically analyzed and catalogued the colors in various geographic regions, has described how each nation, town, and village has its own particular chromatic identity. In his own professional formation it was important to discover the difference between the Western color of his native French Normandy and the Japanese color of Kyoto where he later studied [11].

3.2.1 East versus West

One of the authors grew up in Lugano (Switzerland), while the other grew up near Kyoto (Japan). Both cities have been architecturally influential and have important buildings. Lugano and it environments have been the home of the architects of Rome and St. Petersburg, Francesco Borromini being the most famous. When these architects came home in retirement, they applied their knowledge and experience to the buildings of the local potentates. Over the centuries, this region has produced a number of influential architects, the most well know contemporary being Mario Botta, who has changed Lugano's color by bringing back terra-cotta as the main exterior color for large commercial buildings. Botta is also well known for his analytic functional placement of windows and tight design of interior lighting. With this background, it is easy to understand how Luganesi have a strong opinion on architecture and color.

Kyoto — as the capital of Japan for more than Thousand years — bears a strong role in defining Japanese architecture and its colors. As noted by Akita [1], the colors of Kyoto are the green with landscape, brown with old wood buildings, and vermilion as an accent color in structures. Akita found that three colors are appropriate for the color of a wall in Kyoto: brown (ju-raku), reddish brown (ben-gara), and vermilion (shu-nuri). Paint as a protective coating of houses came to Japan only recently, explaining the importance of wood color; the first major painted building has been Kyoto's 1895 Heian Jingu (Shrine), in which the paint's color is vermilion.

We have seen in Section 3.1.3 on page 13 how Westeners use color to bring extra life to things. The Japanese use color to make things fade towards nothingness. As Kengo [9] exposes, Japanese use color not to create visual light but to intensify the natural effect of light. In an apparent contradiction —when the natural effect of light is weak or non-existent — in Japan architectural structures can be painted with vivid colors, hiding the original material and its latent effect, making even shape secondary to color.

We compounded the tension brought by this apparent contradiction with a violent dialogue between Japanese and Western color schemes.

3.2.2 White and off-white interiors

Before the development of modern hygiene in the last century and climate control devices such as central heating and air conditioning in this century, pests and molds were a major problem in living spaces, especially kitchens and bathrooms where steam is formed. For ages the remedy had been to regularly limewash walls, because slaked lime (water reacted with calcium oxide) is a caustic alkaline substance. Slaked lime (quicklime) is white, which brightens rooms that receive limited light though small windows (insulation is also a modern conquest) or from dim artificial light sources. Other rooms were often painted in muted colors.

In the 30s and 40s, Fillacier first introduced the concept of interior color schemes where vivid colors are in a dynamic equilibrium [14]. Unfortunately, around 1955 white walls began to conquer interiors, reaching a peak in 1975 and only receding very slowly [12]. White is a convenient color for those insecure in their approach to color, because it does not clash with any color. Although white is a "safe" color, it is also psychologically sterile; Mahnke and Mahnke have devoted an entire chapter of their book [12] to a case against white in interiors.

For our scheme we decided to find the most dynamic equilibrium. Yet, a living space must also be a peaceful environment where one can find calm and serenity after a day in today's frantic office world. We established a basic static equilibrium rule by following the recommendation of Nemcsics [13] that the ceiling should be lightest and the floor darkest, leaving the wall colors of a lightness between those of the floor and ceiling for a pleasant feeling. Since the floors are made of a light natural oak, to maximize the dynamic range in which we could choose wall colors, we decided to use a white designer base for the ceilings, if possible with titanium brighteners.

3.2.3 Color for a study

First we worked on the scheme for a study. We decided to keep the exterior trim color S 0510–B70G inside the room. Trim includes all casements, sashes, doors, baseboard, and built-in book shelves.

To further strengthen the interior-exterior relationship, we decided to keep the walls in the same hue as on the exterior, i.e., Y70R. Browsing a Patricia Guild book on interior design, the photograph of a room with hardwood floor, a bright white ceiling, and a vermilion wall was an immediate attention getter, because it was so reminiscent of Heian Jingu's "shu-nuri." We were quickly able to settle on a vivid S 0550–Y70R, which is on the locus of the brightest colors for this hue (see Figure 4 on page 9); this brightness was constrained by the floor's luminance.

3.2.4 Living room color

The living room is decorated with Japanese furniture and prints, combined with neutrally colored Italian furniture. The room receives light from three cardinal directions plus a skylight in the ceiling. The strong presence of light as a modulating element calls for a more subdued color scheme that can intensify the natural effect of light as commanded by the Japanese tradition.

The first step to diminish the impact was to approximately switch the proportions of yellow and red in the wall color, keeping the nuance from the first room to maximize the continuity in the color scheme. Hence, for the NCS color specification for the living room walls we settled on S 0550–Y20R.

To increase the dynamism, we decided to add an alternate wall color for some walls in the living room. The idea was to choose a bright and light color at the entrance, to form a virtual atrium creating a sequence for the person entering the house from the door's chromaticness to a bright but muted intermediate color when the house is entered, leading to a room of the same chromaticness as the door.

To minimize the parameters in the color scheme, while keeping a hue contrast to the dominant wall color, the hue for the alternate wall color was to remain the Y70R of the exterior wall and the study's wall. For the nuance, the brightest and least chromatic sample in the NCS color atlas fixes this alternate color in the scheme to S 0505–Y70R. We found 0510 would have been too strong.

The room's dynamism was kept in bounds by using the alternate color for all trim, instead of the contrasting color used in the study. Also the bathrooms, bedrooms, and their trim was painted in this alternate color, except for the white ceilings. The molding was also painted in white to optically elevate the ceilings.

Table 1 summarizes the selected color scheme. The cylindrical CIELAB coordinates have been obtained by measuring the samples in the NCS color atlas in 5 locations each (corresponding to the spots of a dice showing the number five) and averaging the results. The viewing conditions are the 10˚ CIE standard observer, illuminant D_{65}, and the perfect reflecting diffuser for the white reference.

TABLE 1. Color scheme for a house

Color function	NCS specification			CIELAB
		Lightness	Chroma	Hue
Exterior wall	S 4010–Y70R	60	12	50
Exterior trim	S 0510–B70G	93	9	166
Interior wall study	S 0550–Y70R	71	50	43
Interior wall living	S 0550–Y20R	82	57	73
Interior wall alternate	S 0505–Y70R	92	8	67
Interior trim	S 0505–Y70R	92	8	67
Main door	S 4050–R20B	28	39	2
Ceilings	S 0000–N	100	0	0

The color scheme is represented graphically in Figure 9. The left side indicates the hues and the chromaticness, while the slice on the right indicates the nuances. The nuance 0510 was chosen because the nuance 0505 is not available in the color atlas for the particular hue of the exterior trim and 0510 would have been too chromatic for the wall alternate and interior trim; with this exception, there are four hues and four nuances in this scheme of seven structural colors plus white. These nuances are at only two blackness values and two chromaticness values.

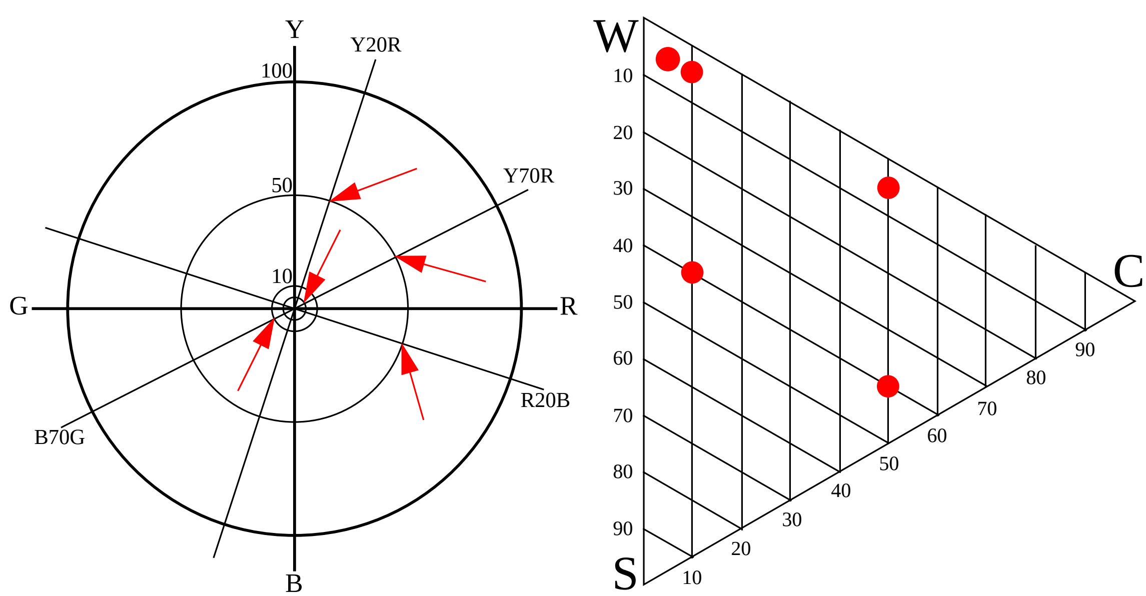

FIGURE 9. Graphical representation of the data in table 1.

3.3 Color interpretation

3.3.1 Japanese view

The scheme as a whole is not Japanese, as this would have to be dominated by a dark brown and white. All we can do is look at colors individually; we have already seen how the color for the study interior wall is an immediate reference to Heian Jingu's "shu-nuri."

For the other colors we can refer to Kobayashi's color image scale [10], which is a popular tool in Japan. We could look up close matches between NCS atlas patches and patches in the color image scale, but the pocket booklet sold here in the USA is printed with ordinary CMYK process colors, which is not sufficient for colorimetry.

The exterior wall color is a less chromatic version of rose gray (R/Gr in Kobayashi's notation), which he describes as follows. "This is a gray color, with a slight tinge of red. It is pleasant and calm, with a warm feel to it. […] Combined with light grayish or light tones, it is gentle and elegant, while in combination with dull or deep tones, it gives a Japanese effect, pleasant and sedate." In this sense, the dynamic balance of our vivid color scheme is very non-Japanese.

The other colors in our scheme do not have close matches in the color image scale. The color that has some similarity to our "interior wall living" color is Gold (Y/S). Kobayashi explains that the Japanese name for this color evokes ripening rice and is associated with nature, contrary to the Western association with luxury. Used with vermilion, it has a luxurious and substantial appearance that used to be popular with the merchants of Osaka. When suggesting color schemes, Kobayashi combines this color with hues of similar nuance.

3.3.2 Western view

We have discussed at length the exterior wall color and how the color scheme was built. Mahnke and Mahnke describe the character of colors when applied in interiors on ceilings, walls, and floors. The main interior colors in our scheme would be characterized as follows:

Interior wall study. Warm, luminous. Has livable charm. Reflection on the skin may enhance some skin tones.

Interior wall living. Warm, exciting to irritating.

Interior wall alternate. Aggression-inhibiting, weak, sweet.

Ceilings. Empty. Helps to diffuse light sources and reduce shadows.

Statements on single colors are of very limited usefulness. Their foundation can also be subjective; in fact, the living room has a more sedate feeling than the study, in part because of the color itself (although Table 1 reveals that despite a constant nuance, the living room is 9 jnds lighter and 7 jnds more vivid), in part because of the opposite choice in the trim color. Maybe the dialogue between “irritating” and “aggression-inhibiting” walls and their correct geometry created just that dynamic balance we were looking for.

Readers who wish to study in depth the analysis and synthesis of color schemes in architectural applications are urged to consult Nemcsics’ book on color dynamics [13]. In our project we did not consider this work because it is based on the Coloroid Color System, while our intent was to exercise the Natural Color System.

4.0 Paint selection

When the color scheme was complete, the next task was to find actual paints. This task required the solution of two problems:

1. In the last paragraph of Section 3.1.2 on page 12 we mentioned that we wanted a paint with a spectrum that has inflection points, so that the illumination modulates the exterior walls. In Section 3.2.1 on page 14 we saw how in Japanese interiors color is used to intensify the natural effect of light. Consequently we wanted a similar spectral characteristic of numerous inflection points, and possibly steep slopes, also for the interior paints.
2. In the USA paints are not specified with the NCS notation, so for each color in our scheme we had to find an actual paint.

The first decision was that even before painting, on the walls that required plastering we would specify the most textured application that the plasterer was offering. This texture would create local shadows, which would be tinged with the complementary color of the illumination during daylight. We further carefully controlled the geometric appearance parameters by consciously specifying the sheen for the various paints: ceilings flat, walls eggshell (velvet), trim semi-gloss (satin), and main door high gloss.

The second decision was to use only colors from the manufacturer’s standard formulary as demonstrated in paint chips. We anticipated several advantages:

1. The paint chips can be used as proxies for the actual paints at a considerable saving of time and money.
2. It is not necessary to store spare paint for subsequent patching and touch-up jobs, since a color would be available for many years.
3. Standard recipes are likely to be robust because they are based on entire units of the pigment dispenser. Thus two cans of paints bought on different days would produce colors that match with a high probability.
4. We speculate that the manufacturer has carefully selected recipes that use a low number of compatible pigments and therefore maintain a high chromatic purity.

We assumed that paint manufacturers apply due diligence in the manufacture of the paint chips, i.e., that they would use pigments closely matching those in the actual paint. This assumption allowed us to take the free chips to our laboratory and measure them right away, without having to buy a pint of paint, apply multiple coats and letting each dry, before being able to perform measurements in the field. We also assumed that the manufacturer would be able to apply a more uniform and consistent paint coat than we could. We evaluated a large number of paints because we could easily feed the colorimetric data directly in a spreadsheet for evaluation.

4.1 White paint

For the white paint we used our finger to smear some paint on a piece of bristol grade paper. Under the light source of the store's paint chip display we could easily determine the brand with the brightest white. For verification, we applied two coats of two white paints on two adjacent areas of a ceiling, each several square meters in size. The difference in lightness was even more pronounced than on the bristol paper. This difference was so striking that it was not necessary to use any instrumentation. The colorimetry for the sample on bristol is $L^* = 98$, $C^* = 3$.

4.2 Spectral reflectance

For convenience, we decided to limit ourselves to the local neighborhood paint store instead of attempting a systematic survey of paint manufacturers. Our store carried four paint brands: a store brand, two national brands, and a famous designer brand. We ruled out the designer brand because of its high cost and the probability that it was just a repackaged variant of one of the other brands.

Standing in front of the paint chip displays, the difference in the size of the formularies was striking. The two national brands had both large selections, ordered roughly by hue and saturation. The store brand had a much smaller selection, covering a good size color gamut; there was no close match for some of the colors in our scheme. The designer brand was instead very small and the colors were grouped by emotional criteria, with no apparent order inside a group.

To compare the brands, we chose one color and compared the chip spectra for that color. For the color we chose the trim S 0510–B70G because it is a light color; it would require small quantities of pigments, hence be harder to mix. To select the chips, we matched visually the sample from the NCS index with the store display. For the spectral quality, we wanted many inflection points and steep slopes so the paint is modulated by the ambient light.

Figure 10 shows the result. The designer brand has a relatively flat spectrum, so it would simply follow the incident light's spectrum. Like the store brand, it has a relatively large hue difference — as computed with (EQ 5) — to the target color, which is due to the limited number of colors available in the palette. In the blue-green portion of the spectrum, national brand 2 had the steepest slope, so we chose that brand for all of our paints.

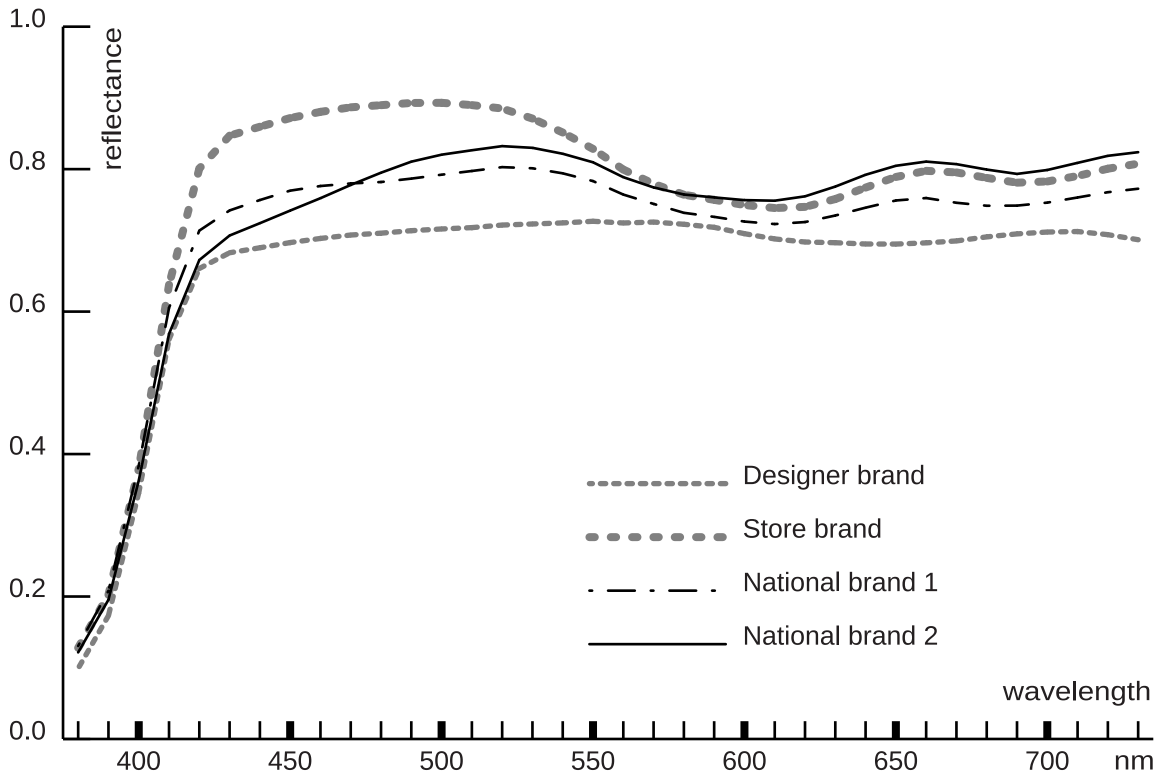

FIGURE 10. Spectral reflectance curves of four paint brands approximately matching the color S 0510–B70G for the trim. The fourth paint has the steepest slope in the dominant range for hue B70G.

After selecting a paint brand, we had to determine the closest standard color for each color in our scheme. We accomplished this task in three steps. In a first step we used the NCS index to visually find the paint colors approximately matching each color in our scheme. In a second step we measured the chips for these colors and determined the closest match in the sense of CIE94, equation (EQ 2) on page 8. The third step was iterative. We bought a pint of the paint, painted an area of about 1 m^2, surrounded it by a trim line, and lived with it for a few days. If not satisfied, we then used the NCS index to find a closest alternate color. To find this alternate color, we used not only the paint chips in the display, but also a booklet with color cards representing standard colors not in the store display. Figure 11 shows the chip's spectral reflectance curves for the selected colors.

Because of this third step, the color finally selected was not always the one closest to the color in our scheme in a colorimetric sense, but the color we subjectively felt looked the best. Therefore, the color difference between each color in our scheme does not truly indicate how reliably USA paints can be used to implement an NCS specification. Instead, this difference indicates how useful the NCS system is to build a color scheme from the stan-

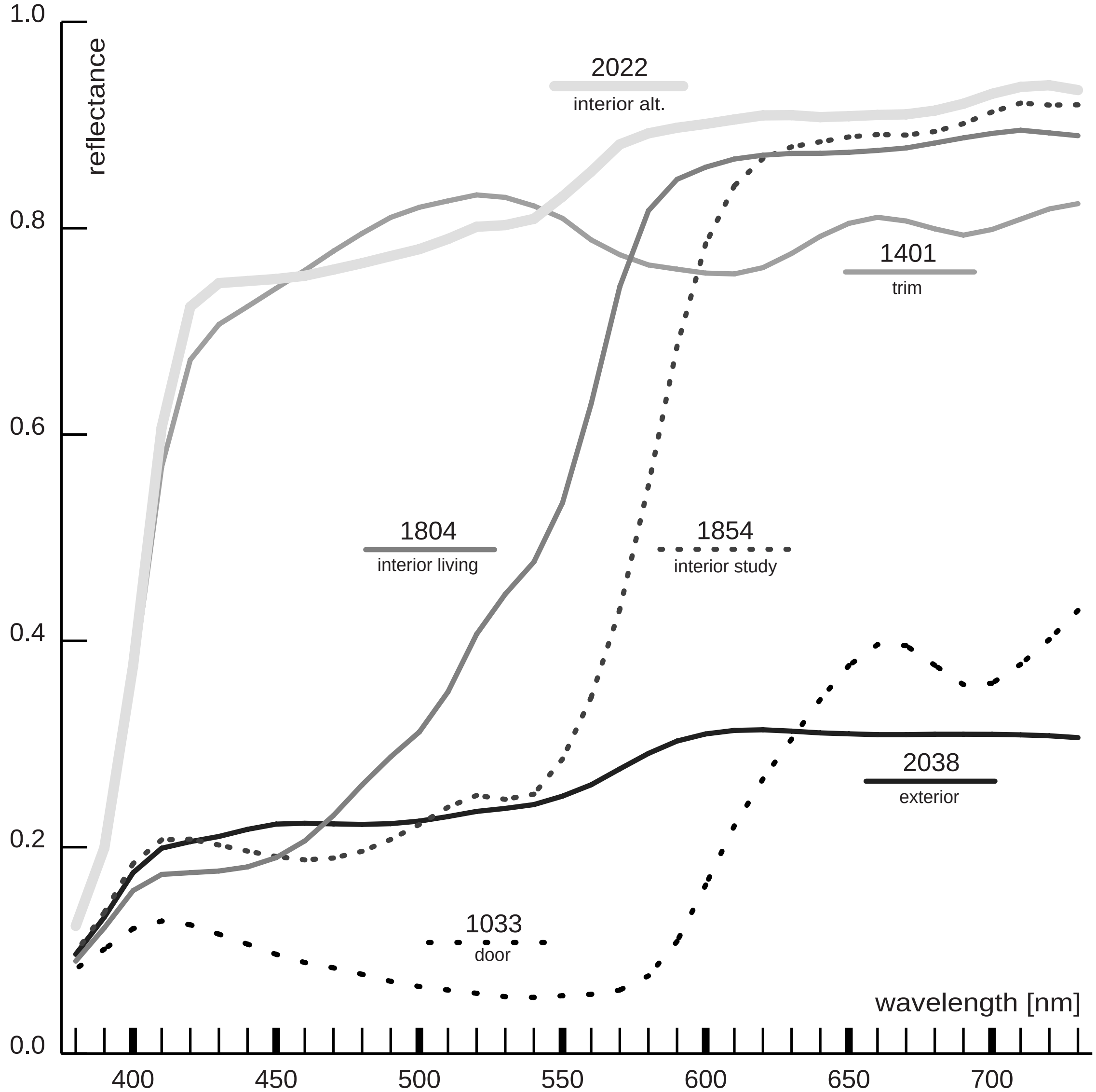

FIGURE 11. Spectral reflectance curves of all selected paint chips. The curves are interesting, with abundant inflection points and steep slopes, which together help illumination modulating the colors. See Figure 12 on page 25 for the ceiling.

dard palettes of colors offered by USA manufacturers. Table 2 lists the paints chosen and the color difference to the NCS specification.

TABLE 2. Selected paints form those available from "national brand 2"

Color function	NCS specificn.	Paint chip	CIELAB				Chip to NCS		
			L*	C*	h	CIE94	ΔL*	ΔC*	Δh
Exterior wall	S 4010–Y70R	2038	58	10	51	2	2	3	0
Exterior trim	S 0510–B70G	1401	91	7	139	4	1	2	-4
Wall study	S 0550–Y70R	1854	71	48	43	1	1	1	0

TABLE 2. Selected paints form those available from "national brand 2"

Color function	NCS specificn.	Paint chip	CIELAB			Chip to NCS			
			L*	C*	h	CIE94	ΔL*	ΔC*	Δh
Wall living	S 0550–Y20R	1804	81	52	70	2	1	5	-3
Wall alternate	S 0505–Y70R	2022	93	8	67	1	-1	0	0
Interior trim	S 0505–Y70R	2022	93	8	67	1	-1	0	0
Main door	S 4050–R20B	1033	37	33	0	9	-9	6	-1
Ceilings	S 0000–N	designer white base	98	3	102	3	-2	3	0

The color differences in Table 2 were computed using (EQ 2) on the full precision[6] data, not the values listed in this Table and in Table 1 on page 17. Therefore the differences in the perceptual correlates do not add up to the total color difference due to rounding. The viewing conditions are always illuminant D_{65} and 10˚ observer.

4.3 Chips and paints

The largest difference was in the color for the main door, for which we were able to find only a darker color in the manufacturer's palette. We believed this would be a smaller problem than might appear at first, because we specified a high gloss paint. High gloss paints are very transparent, and we used a pure white undercoat to hopefully obtain a total color appearance more closely matching the specified color.

The other colors matched quite accurately the corresponding NCS colors in the designed scheme. The color difference between the perfect reflecting diffuser and a real physical paint chip is of course somewhat large. Since we finally judged painted colors and not chips, we need to evaluate the color differences between painted colors and the specified NCS colors. To gauge the validity of using paint chips as proxies of the paints, we also have to compare the painted colors to the chips colors, especially since we have effectively exploited the transparency of some paints.[7]

The colorimetry for the painted colors was somewhat tricky because of the textured plaster. The best solution would have been to use a uniform light source to illuminate a sufficiently large portion of the wall and measure it with a spectroradiometer. We judged this to be an overkill for a house painting project and resorted to a simpler approximate method. We used a spectrophotometer with a small aperture (4 mm) and tried to find possibly flat portions in the plaster. For each paint we made 10 measurements in different locations and averaged them, with exception of the living room and the main door, which were outside the reach of a spectrophotometer tethered to a computer. Table 3 shows for each color the

6. The accuracy of the instrument used was 0.3 CIELAB units, determined in conformance to ISO 9001.
7. For the exterior walls we used two undercoats, tinging the second one with the final color. For the interior walls we applied several coats to obtain complete coverage.

average paint color and the standard deviation. The standard deviation of the designer white base is the best indication for reliability of the measurements.

TABLE 3. Paints applied to surface

Color function	Applied paint	CIELAB			Standard deviation		
		L*	C*	h	L*	C*	h
Exterior wall	2038	63	9	49	0.14	0.11	0.33
Exterior trim	1401	90	8	125	0.34	1.26	8.40
Wall study	1854	71	48	43	0.02	0.13	0.06
Wall living	1804	80	54	72	n/a	n/a	n/a
Wall alternate	2022	94	9	72	0.44	0.82	1.32
Main door	1033	28	37	9	n/a	n/a	n/a
Ceilings	designer white base	96	2	98	0.37	0.10	2.54

Finally, Table 4 shows for each paint the color difference to the NCS specification and to the paint chip. The exterior wall turned out lighter than anticipated, the exterior trim somewhat greener, and the door much darker. Deep high gloss paints appear to be particularly difficult to predict, but fortunately the final color was pleasing and integrated in the actual scheme. In conclusion, the NCS color system is a useful tool to design a color scheme for painting a house.

TABLE 4. CIE94 color difference from paint to NCS and to chip

NCS specification	Paint to NCS				Paint chip	Paint to chip			
	ΔE	ΔL*	ΔC*	Δh		ΔE	ΔL*	ΔC*	Δh
S 4010–Y70R	4	-3	3	0	2038	5	-4	0	0
S 0510–B70G	6	2	1	-6	1401	2	1	-1	-2
S 0550–Y70R	2	1	0	3	1854	2	0	-1	3
S 0550–Y20R	2	2	3	-1	1804	2	1	-3	2
S 0505–Y70R	2	-2	0	1	2022	1	0	-1	1
S 4050–R20B	15	14	-5	6	1033	10	9	-4	5
S 0000–N	3	-2	3	0	designer white base	3	3	1	0

The big disappointment was the exterior wall color. With L* = 60 and C* = 12, the NCS sample chosen was at the light side of our preference. With L* = 58 and C* = 10 the paint chip was slightly darker and less vivid, so were able to (almost) compromise on the color choice. However, with L* = 62 (and C* = 9) the exterior wall resulted too light. The next darker color from that paint brand would have been 2039, with L* = 40 and C* = 8, which would have been too dark. In retrospect, we should have resorted to a different paint brand, since the store offered a choice.[8]

In fact, Figure 12 illustrates that the spectral reflectance curve for this paint is not particularly interesting. The top curve is the reflectance of the designer white base before any pigment is added. The chip's reflectance is translated down at a more or less constant displacement with respect to the applied paint. Adding black pigment would have corrected the paint's color, however this would no longer be a standard color and make it harder to buy a matching paint later. We have to admit that for this paint we have failed our goal of selecting a paint with a spectral reflectance curve that get strongly modulated by available reflected light.

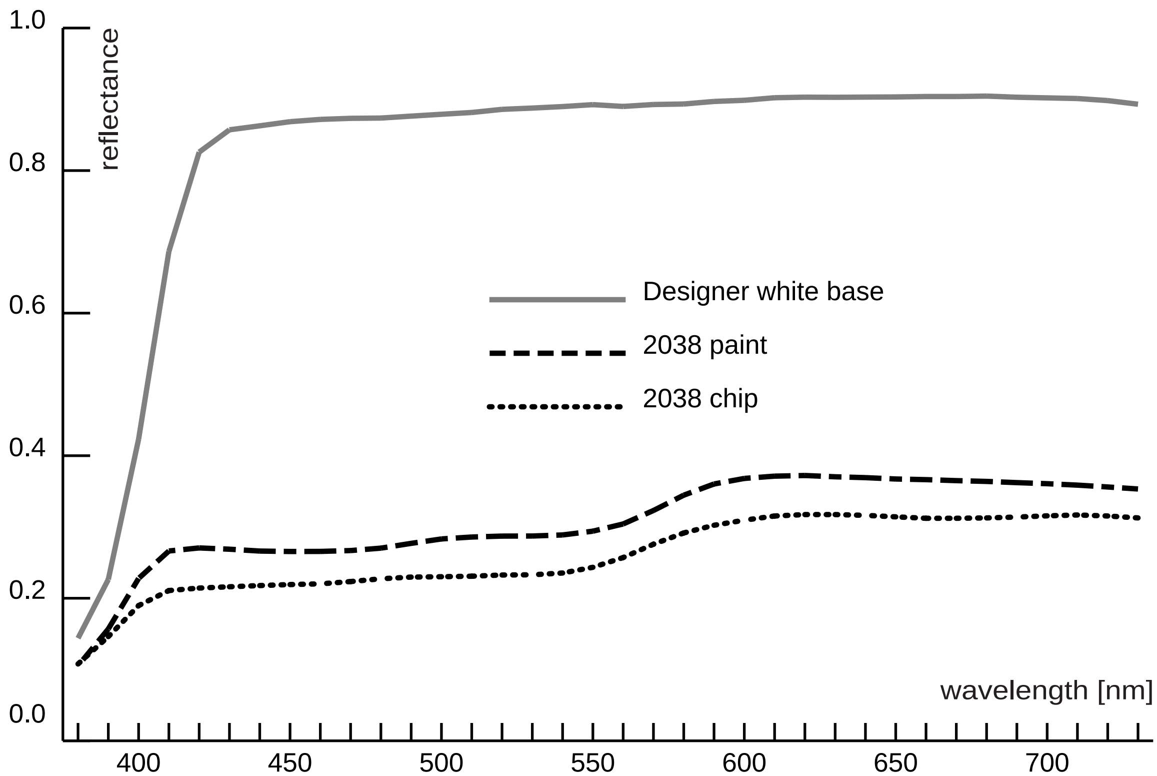

FIGURE 12. Spectral reflectance curves for the "designer white base" paint used on ceilings and for the exterior wall, both chip and paint.

4.4 Matching by computer

Unintentionally, we were able to test also the usefulness of the computerized color matching offered by most paint stores. When we ordered new book cases for the study, we specified the exact brand and color number to the cabinet maker, explaining why we did not want a substitute brand or paint type. Unfortunately the cabinet maker had too much faith in computers. Although he swore he used the specified paint, the match is not good. Colorimetry reveals that although the lightness and the chroma are matched quite accurately,

8. Since this color choice was critical, we might also have fallen victim to the effect noted by Fridell Anter that the perceived color tends to have less blackness than the inherent color [6].

there is a hue error of 6 CIELAB units in the direction of blue and away from green. While compared to the NCS sample the original paint is slightly too greenish, the matched paint is decidedly too bluish.

The graph in Figure 13 reveals exactly what might have happened. The paint appears to have been matched from a chip of the specified paint. The algorithm commonly used in these systems is to measure the specimen under a number of illuminants. The computer then uses a database with the standard recipes of the paint manufacturer providing the matching system to find a recipe that closely matches the sample under the illuminants. Only if no close match can be found, the system computes a new recipe.

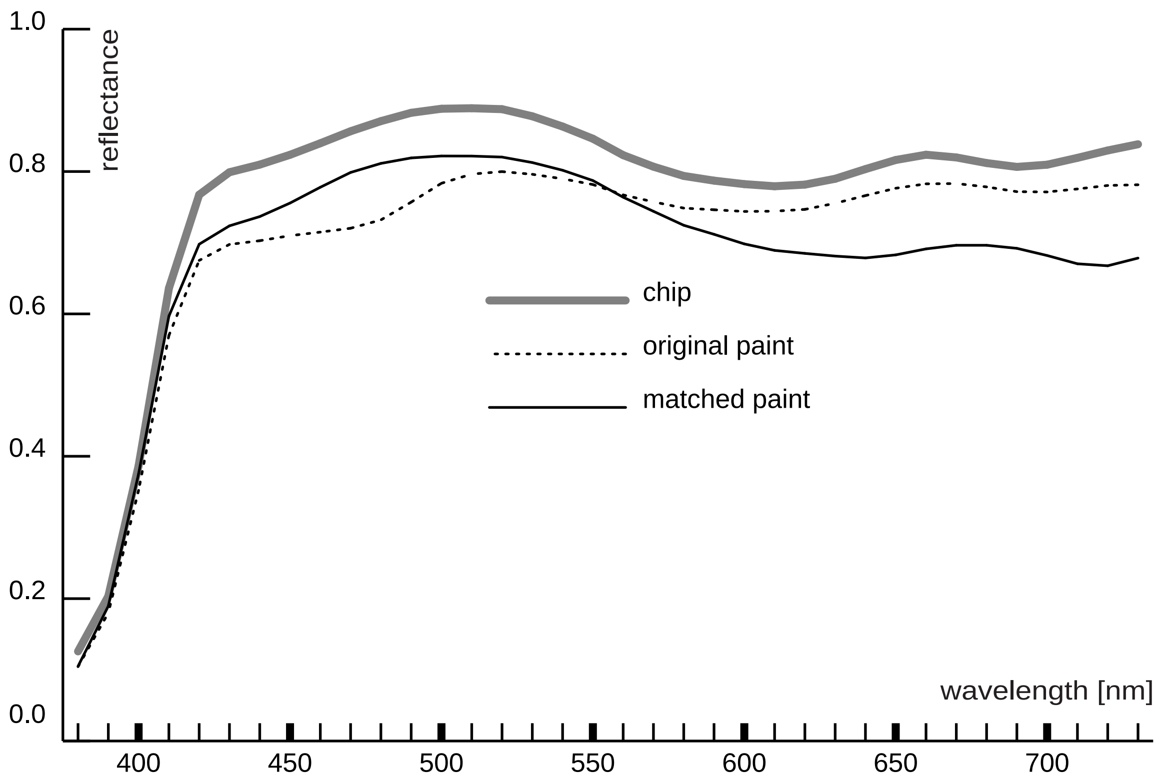

FIGURE 13. Spectral reflectance curves of a paint, its computer match, and a chip of the first paint.

The original paint had a spectrum different from its corresponding chip, and the color matching computer was fed an incorrect input. By chance, the system had a standard recipe close to that used for the original manufacturer's paint chip and it inferred a match. Indeed, the spectral distribution of the original paint is even better than the chip, enhancing the light modulation. Since the study has four doors painted in the trim color, this creates a very annoying clash of colors. While the trim color is a delicate light blue with a hint of green that is modulated by the reflections from the vermilion walls and the light from windows on two sides, the color of the book cases is just a plain and boring baby blue. The tungsten light in the evening accentuates this total appearance.

5.0 Conclusions

We have been able to successfully use the NCS color atlas and index to design the color scheme for a house, encompassing both the exterior and the interior. Using an atlas has allowed us to design a scheme representing a strong dynamic equilibrium. USA manufacturers offer a sufficiently good selection of standard paint colors that a color scheme specified with NCS can be accurately realized with standard paints. However there are differences in the spectral compositions of the paint chips and the paints themselves, so that colors should not be computer-matched from paint chips.

It is still necessary to test a paint color by applying it to an area at least a square meter in size, because this is the only way to appreciate the total appearance of a color. However, the atlas simplifies the choice of an alternate color if the first color is not satisfactory.

Color is modulated by incident light, which in the real world is highly variegate. An interesting spectral distribution in the paint will lead to an interesting wall, that is modulated by the available light. It might be interesting to create a tool that can predict this effect. We tried to compare the colorimetry at illuminant A with the colorimetry at illuminant D_{65} for the paints in our scheme, but that was not a good predictor of the final effect. It is probably necessary to convolve the reflectance curves with a number of incident spectral power distributions and study the change of the reflected spectral power distributions. The difficulty in this is that the incident spectral power depends upon the ambient.

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