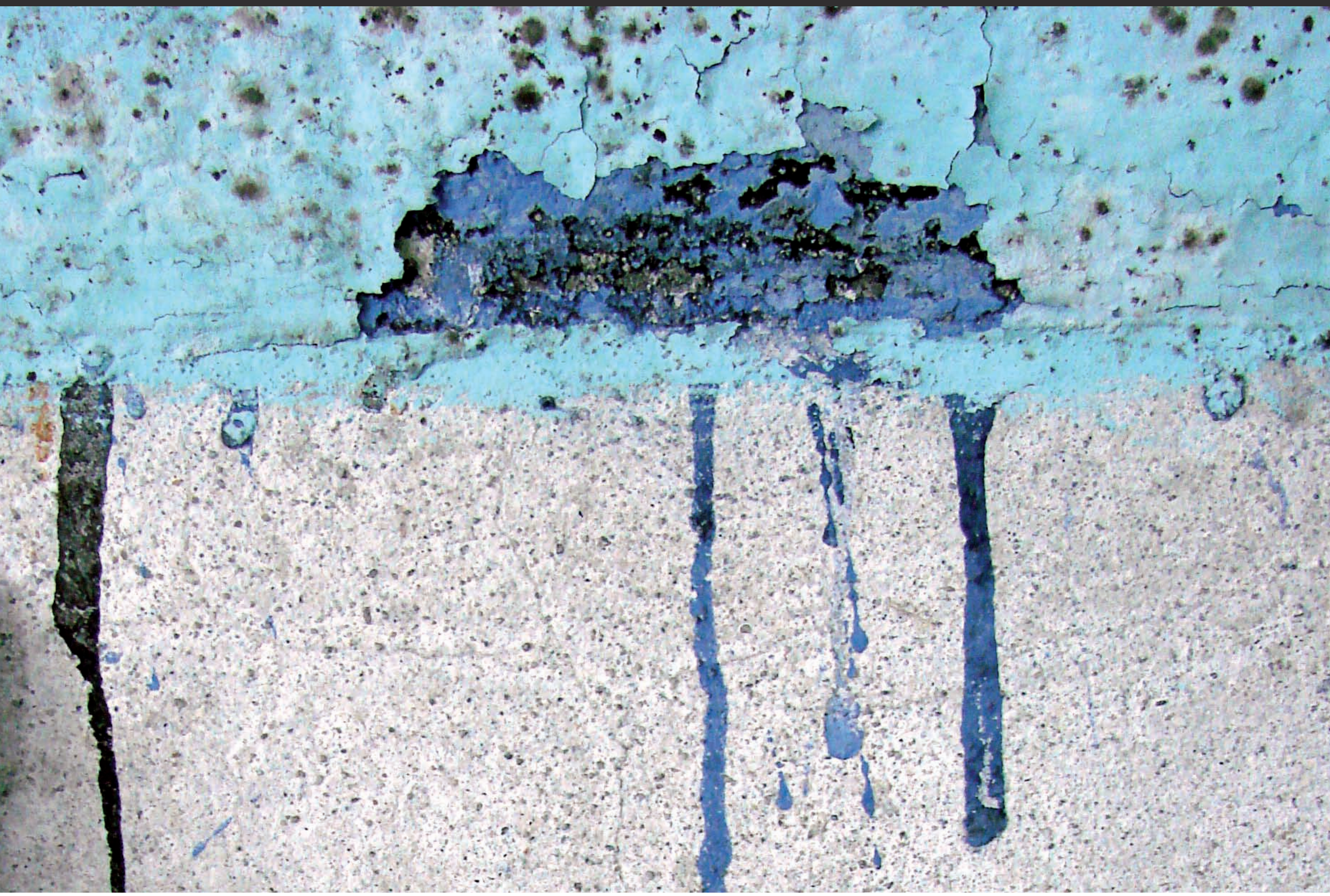
Scuola universitaria professionale della Svizzera italiana

La conservazione delle policromie nell'architettura del XX secolo

Conservation of colour in 20th Century architecture

a cura di | edited by Giacinta Jean



SUPSI | Nardini Editore

Identification and translation of 20th Century colors to modern industrial paints

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Architectural color interventions are commonly based on paint specifications that include a microchemical and/or stratigraphic assessment of the sample and an assessment of the color hue based on comparison of a freed sample to reference colors of an existing color notation system. The reference colors are the surface colors in the color space defined by a color notation system such as NCS[1] or Munsell.[2] Once a reference color has been specified, it is translated to a paint formulation based on modern pigments in the appropriate binder. Neither the pigment composition nor the granulometry of the original paint are considered and restored. The loss of color information inherent to these methods of assessment and consequences for efforts to restore an architect's polychromy are topics in this publication.

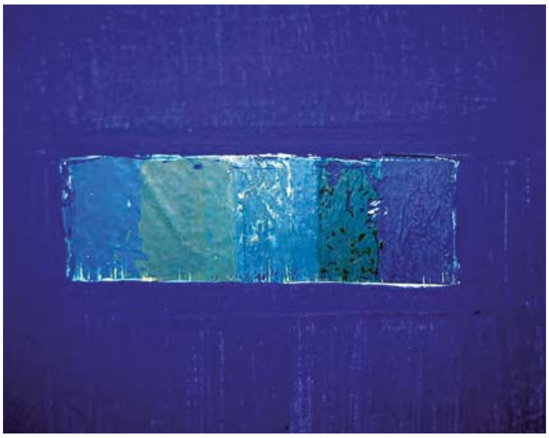
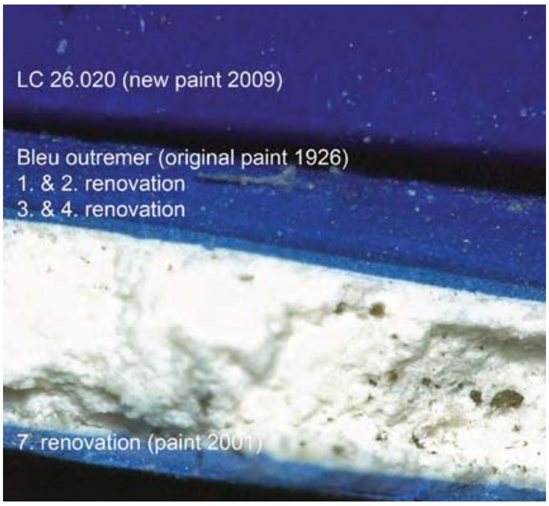


Fig. 1: Villa La Roche, passage from main hall to maid's room. Paint layers visible after restorator Ariel Bertrand laid open the paint layers. The colors range from a medium ultramarine blue shade on the left (a blue acrylic paint from 2001) to the sample on the right, which is the original ultramarine blue in glue paint fixed with casein and deepened with bone black in 1925-1926. What causes such differences, how do they affect architecture?

The experimental section describes the color assessment and the restoration of the interior polychromy of the Villa La Roche, constructed by Le Corbusier/Pierre Jeanneret in 1923 to 1925 in Paris. The restoration involved: 1. the definition of the layer to be restored; 2. the chemical and physical analysis of this paint layer; 3. the formulation of a new paint made with the original pigments; 4. the visual adjustment of the historical formulation until it matched the original sample under microscopic conditions; and 5. the formulation of a modern paint optimized in terms of non-toxicity, history and modern conditions of use in the renovated building.
The color identification, reformulation of the original paints, and translation to modern paints appropriate to the flow of visitors through Villa la Roche is described in detail. The availability of paint samples that can be analyzed under a light microscope provided for, we consider the method described and contrasted to conventional comparative methods in this publication to be the most reliable method now available for the restoration of an architectural polychromy.

The common procedure for the restoration of architectural color

The methodologies common in color restoration include 6 main stages: 1. freeing a window by scratching away more recent paint layers (Fig. 1); 2. selecting the layer to be analyzed and restored; 3. sampling of the selected paint layer; 4. microchemical, stratigraphic, chromatographic and/or spectroscopic analyses of the sample; 5. matching the color visible in the freed window to a reference in a color notation system, most commonly NCS, which will be used in the subsequent



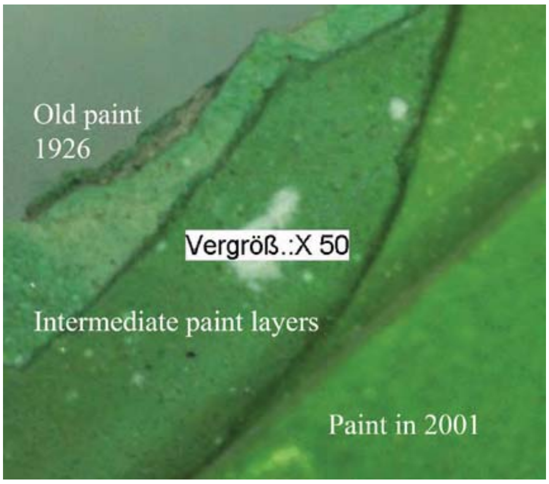


Fig. 2: Detail from a light microscope photograph of a cross section of the blue wall leading from the entrance hall to the maid's room in Villa La Roche. 50x magnification. The top band labelled "LC 26.020 restored" shows the glue-emulsion paint used in the restoration in 2009. Under it is the cross section of the two oldest paint layers from 1925-1926. Note that the old paint layers look deeper in the cross section here than in the laid open window in Figure 1.

Fig. 3: Light microscope view of a green paint sample from Villa La Roche. The 1920s glue paint under more recent paint layers was made with coarse Prussian blue and chromium yellow pigment particles (corresponding to the pigment *vert anglais*), the most recent green acrylic paint was made with nanometer particle size organic pigments. Color nuance, paint structure, light activity and the spatial effects of the color in the small, dark room were affected.

discussions; 6. reproducing the reference color using an appropriate binder.

The restored paint is then assumed to be a non-toxic, modern variant of the original one. The coloristic and spatial effects in particular are assumed to correspond to the effects once visible in the architecture.

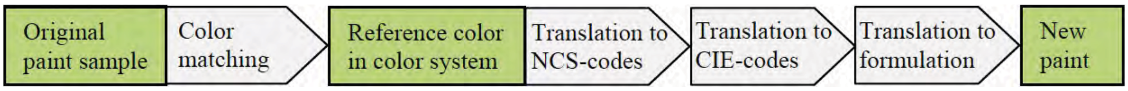
The techniques used in the first four stages yield useful information on the paint materials once used in the architecture. Considerable information on the binders and pigments can be obtained. Although the samples available for analytical procedures are usually mixtures of several paint layers, the results often allow the researcher to preclude certain pigments and give preferences to those that align with the analyses. The value of the information to be gained through the application of these methods is unquestioned. Their limitation lies in the fact that none of the common analytical procedures can be used to reconstruct color appearance. Even specific results, such as "ultramarine blue with bone black", do not allow the color hue[3] and its level of saturation to be defined. This is addressed in stage 5, matching the laid-free color to a reference in a color notation system. In stage 6, this information is back-translated to a new paint.

Most procedures of color restoration today involve these two translations, the first from the original sample to the reference in the color notation system, and the second, from this color notation system reference to a paint to be used in the restoration. Interventions are thus concerned with the restoration of color appearance using a binder close to the original one, and not with the restoration of color as a light-modulating material.

Error sources in the common procedure for the restoration of architectural color

The physical interaction of pigments with light, which is modified by the light refraction of the paint medium, determines the optical, spatial, and psychological effects of a color. Shifts in color hue and in the materialization of the color inevitably affect the quality and the intensity of the interactions of surfaces and volumes with light. As can be seen in Figures 2 and 3, sequential res-

Fig. 4-5: View under the light microscope of a paint chip taken from the single radiator in Villa La Roche that was never repainted. Optical matching led us to believe that the original oil paint was a dark umber with a deep, gray-brown appearance (Fig. 4). Cleaning the sample with potassium hydroxide (KOH) and color matching showed us that an oil paint pigmented with lead white and ivory (bone) black was used, not umber (Fig. 5).

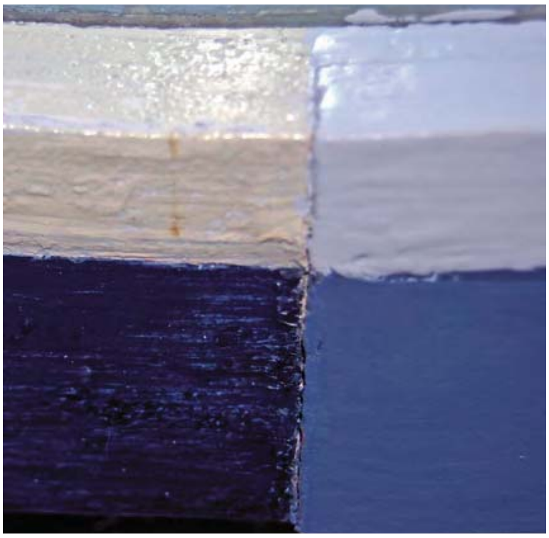


Scheme 1: Graphic representation of the materials and processes behind color matching, in which an old paint surface is color matched to a reference in a color notation system, and this reference is translated to a new paint.

toration efforts resulted in a shift in the coloration, pigmentation, and materiality on the interior walls of Villa La Roche. As mentioned above, such changes in appearance, pigment and material can be shown to affect the light in the space; thus, they change the perception of space itself. The shifts in color were not intentional, however, and they were not caused by poor craftsmanship. The sources of error at work here are: 1. mechanical damage to the paint surface, causing errors in color matching. This source of error arises in the first process in the graphic below. The result is that the wrong reference is selected and translated to modern paint; and 2. the three translation processes shown in the graphic below, from paint material to reference color to spectral color to a new paint material. These translations match the original to references that may not be close to them in the first place, immaterialize color and relate it to coordinates in a color sphere, translate the coordinates to spectral color coordinates, and rematerialize these to a new, different material.

The consequences of mechanical damage to paint surfaces

One inevitable limitation of any color matching procedure arises from the mechanical damage to the laid open paint surface caused by scraping away more recent paints. The scratched paint surfaces are inadvertently damaged and look different – lighter or darker – than the cross section under the light microscope. Comparing the blue paint seen in the window in Figure 1 to the same blue paint seen in the cross section under the light microscope in Figure 2 shows this difference. The new paint surrounding the laid open window in Figure 1. appears darker than the original paint layer. The reformulation of the paint from 1926 according to the color seen in the cross-section of the layer (Fig. 2) showed that the ultramarine blue paint was quite dark, darker than the ones used in previous renovations. It was also darker than the one we would have used in the restoration had the laid-open window been the only source of color determination.
Figure 4 shows another interesting example of the false conclusions that can be drawn from the visual inspection of surface color. One radiator in Villa La Roche was never repainted. A chip from this radiator was used



Figg. 6-7: Blue woodwork in Maison Blanche.
Figure 6 shows the original paints from 1912 and, on the right, the paints used in the renovation. The binders are similar: linseed oil in 1912, modified natural oils in 2005. The latter results in thicker paint layers, but the refractive index of the two binders and the gloss are similar. The deviation of new from old is obvious; the appearance of the woodwork in Figure 7 would be rather different – more elegant, less colorful – if the original paint materials had indeed been restored. This kind of shift is typical. How can we explain it? (Fig. 7: Heinrich Helfenstein, Zürich, and *Association Maison Blanche*, AMB, 2009).

to match colors. Our initial assumption was that the oil paint used for the radiators was a dark, warm, brownish gray. Since it was known that the pigment *terre d'ombre naturelle* (natural umber) was purchased for use in the interior of the Villa, this was a logical conclusion.[4]
Or not? A closer look at the paint chip showed us: 1. that the paint was an oil paint, no resins were added, and the oil paint could be removed and cleaned easily by treatment with strong base (KOH); 2. cleaning showed that what appeared to be a rough paint was a mixture of rust and a gray oil paint made with lead white and ivory black. The restored color LC 26.010 *Gris foncé La Roche* is gray; it is significantly lighter and cooler than the one proposed initially.
Damaged, scratched, or dirtied surfaces alter the optical appearance of the old paint sample, which complicates the identification process. Thus, the first error common in color identification procedures is linked to the quality of the sampling window or color sample. Our identification and translation methods make use of a microscopic method of color matching to avoid problems associated with matching a color reference to a damaged paint surface.

The consequences of translations from an old paint to a reference color to spatial coordinates to a new paint

The second error in color identification and restoration occurs with the translation of the (often damaged) paint surface seen in the laid open window to a reference color in a color order system, from there to a spectral color, and from there to a new paint. This source of error is related to color theory and to the way we think about and define color today. It is more difficult to understand. Again, we begin with an example.
Figure 6 shows old and new next to each other on the woodwork of Maison Blanche, a villa built in 1912 by Charles-Edouard Jeanneret (later to become Le Corbusier) in La Chaux-de-Fonds in Switzerland. The house was restored and opened to the public in 2006. Color identification was based on matching laid open paint layers to reference colors in the NCS fan deck[5] and in a fan deck from 1912.[6] The original paints were

not analyzed for pigment composition. The paints used in the restoration of the interior and the exterior polychromy were adjusted to the reference hues closest to the color seen in the laid open window using pigments that are available today. This is a common practice in restoration technology.

In Figure 6, the difference between old and new cannot be attributed to the quality of the original paint surface. It is undamaged. The yellowing of the linseed oil is certainly a factor, but it cannot explain the complete shift to a colder white and a much flatter blue. In fact, the shift from one white to another has a different cause than the shift in the blue. The first is an error caused by the ambiguity inherent to color names. The second is an error in method. Both errors result in the incorrect materialization of the painted surface, both alter the effects of the interior polychromy.

The ambiguity inherent to color terms often causes unintentional shifts in colors. White is commonly affected by this. Color terms such as "white" or "yellow" give rise to perceptions – we imagine a white surface or a yellow one. These perceptions reflect color conventions, and color conventions are related to the material sources of color available at any given time in history.[7] What architects have in mind today when they speak of a white building or white woodwork is different from what Le Corbusier had in mind when he spoke of white woodwork, or white facades. Thus, asking a painter to paint window sills white once again, since they were white in 1912, might well lead to precisely the kind of shift seen in Figure 6, in which the lead white common in 1912 was replaced by titanium dioxide white, the predominant white in use today. A color shift from a warm, translucent, light reflecting hue to a cold, opaque, light scattering[8] hue is the result. Le Corbusier's white and the conception of white in 1920 was related to the color of cream.[9] The conception of white today is colder and more clinical. The pigment titanium white is different in its light interactions and spatial effects than lead white, zinc white, or slaked lime and chalk – the three whites common in Le Corbusier's days. Since white is considered to be clean and neutral, it is common to think that shifts in white do not affect architecture.[10]

Precisely this ambiguity in color terms led to the widespread use of color notation systems. While avoiding the pitfall of imprecise color terms, however, they introduce new, persistent problems to color interventions in architecture. The new blue in Figure 6, which is clearly incorrect, is one result.

Since the original blue color was still visible and the surface could be easily cleaned, restoration involved color matching and reproduction of what was assumed to be the reference closest to the original hue. The procedure is straightforward: the color sample is compared to the reference color squares in a fan deck of reference colors. A color reference is selected, the binder chosen, and a modern paint that corresponds to hue and binder selection is produced and applied. The identity of the pigment in the new, industrial paint is generally unknown. Since the pigments used in early modernism are not the same pigments as the ones used in modern industrial paints, the specified reference color is reproduced, but not the original material. Is this a problem? What we perceive when looking at a colored surface is caused by a specific color. We do not see blue or yellow or red, we see a particular color. Generalized statements, such as blue is cold, are likely to apply to this particular blue, but the specifics of its psychological and spatial effects are not assessed by such statements. Even the general observations, such as blue is cold, will not apply to every blue. It follows that a change in the coloring material causes a change in the effects of a color. The question remains, how significant the change in the spatial effect of a color caused by a change in the pigments will be? Modern color theories such as NCS are based upon and validate translation procedures to other materials and to spectral color coordinates. This implies that the materialization of color is less important to the spatial and psychological effects of color as the specification of a location on the surface of a hypothetical color sphere. Any blue specified by the same three coordinates is assumed to have the same effects on our perception of meaning and space. High-quality color matching ensures precise communication, precise communication facilitates color restoration: this is the common assumption. This de-facto assumption of the non-importance of pigments to color effects is so common today that it is rarely questioned. Modern quantum physical theory clearly states that this is an incorrect assumption.[11] It is just as clear that the quantification of perceptual changes to space is a difficult endeavor. We argue that efforts to restore a polychromy should therefore use materials as close to the original ones as possible. This avoids material substitutions and thus, potential errors of unknown magnitude. In other words, to get an architectural polychromy right, color hue and coloring materials – the pigments, binders, and granular composition of the paint – should be identified and restored.

We address this concern by: 1. explaining some of the theory underlying standard color notation systems such as Munsell and NCS; 2. describing the limitations of these standard color notation systems in identifying and restoring architectural polychromy; 3. suggesting an alternative method by which more accurate information can be obtained.

The theory underlying color notation systems

The advent of standardized color notation systems in the 20th Century was greeted as a break-through in color communication.[12] The ambiguity inherent to color terms was eliminated by referencing a surface color to a location in a three-dimensional color space. Each location was uniquely specified by three variables. This unique location could be translated back to paint formulations in any specified binder.

Color notation systems attempt to objectify the appearance of color. "Color anarchy is replaced by systematic color description", wrote Albert H. Munsell hopefully in 1905.[13] The color systems group colors according to perceptual descriptors such as the color itself (red, blue etc.), how clear or grayed, and how saturated, white or light it is. The colors are arranged in a color space defined by three axes. These represent the elementary colors black-white, yellow-blue and green-red in the Natural Color System (NCS),[14] which relies on the opponent process of color vision for its physiological base. In the Munsell system, ten hues were defined and spaced equally around the perimeter of the color globe. In both systems, perceptual judgments rather than remission measurements were used to place the standards in the color space. Both systems share the vertical white to black axis. Both systems use notation systems with three independent parameters to place any single color in the color space.[15]

The hues in the Munsell color order system and standardized colors in NCS can be related to each other. One primary difference between the two systems is that the Munsell order system is based on perceptually even spacing between the hues (from red to orange or blue-green to green), whereas the NCS system is based on resemblances to the "elementary" [opponent] colors in its placement of fully chromatic colors on the rim of a color wheel. Red is opposed to green and blue is opposed to yellow.[16] Also, in the Munsell color system, complementary hues oppose each other – magenta is opposed to green and blue is opposed to red-orange. These differences aside, both systems rely on three determinants to describe a color perception, and the following discussion is based on NCS rather than the Munsell system. The limitations we mention will be the same for *any* color order system that differentiates colors using three variables, which are translated to spectral x, y, z-axes, as described below.

In their seminal description of NCS published in 1981, Hård and Sivik write: "to describe a single color unambiguously, three mutually independent dimensions are sufficient".[17] In NCS, each color is described by the three dimensions whiteness, blackness and chromaticness. Chromaticness is the hue and saturation of the color. Reference colors along the three dimensions were selected through the statistical evaluation of visual assessment data in which participants were asked to rank a great number of color samples and to indicate perceptual equivalence. This statistical assessment of such subjective data gathered under laboratory conditions led to the selection of a certain number of reference hues within the color space. The distance between hues was not measured; it was defined in perceptual terms. Thousands of observations were analyzed and compared to spectral reflectance measurements, and these were correlated to some 1400 references which were published as a color atlas.[18] The system was continually expanded and revised, such that there are now 1950 standardized colors in the NCS color space. Algorithms were developed that allow the values of the standard colorimetric system CIE to be translated to the NCS-

TABLE I. NCS notations, CIE tristimulus values (Ill. *C*, 1931 standard observer), and Munsell notations for the NCS aim points with hue B50G.

NCS notation	CIE tristimulus values *X*	*Y*	*Z*	Munsell notation
0010–B50G	86.72	91.95	112.29	9.57BG 9.58/1.34
1010–B50G	65.54	69.68	85.43	0.04B 8.57/1.31
2010–B50G	49.91	53.23	65.57	9.87BG 7.66/1.33
3010–B50G	37.92	40.59	50.28	9.70BG 6.83/1.33
4010–B50G	28.43	30.58	38.13	9.49BG 6.05/1.34
5010–B50G	20.75	22.44	28.22	9.21BG 5.29/1.35
6010–B50G	14.42	15.70	19.96	9.05BG 4.52/1.37
7010–B50G	9.12	10.03	12.92	8.65BG 3.68/1.40
8010–B50G	4.66	5.19	6.81	8.08BG 2.66/1.42
9010–B50G	0.89	1.01	1.36	6.68BG 0.85/1.02
0020–B50G	75.81	84.03	106.50	9.76BG 9.24/2.64
1020–B50G	56.58	63.08	80.63	9.81BG 8.22/2.71
2020–B50G	42.38	47.58	61.43	9.63BG 7.30/2.73
3020–B50G	31.50	35.65	46.57	9.41BG 6.46/2.71
4020–B50G	22.90	26.19	34.70	9.13BG 5.65/2.73
5020–B50G	15.97	18.50	24.93	8.83BG 4.86/2.77
6020–B50G	10.32	12.12	16.67	8.64BG 4.02/2.67
7020–B50G	5.65	6.75	9.51	8.04BG 3.04/2.54

Fig. 8: Computed equivalences NCS, CIE-tristimulus and Munsell notations (F.W. Billmeyer Jr., A.K. Bencuya, *Interrelation of the Natural Color System…* cit., p. 246). The translation from spectral measured values to "perceptual" values based on the evaluation of pigmented paint chips is based on Graßmann's formulation of Newton's laws of optics (see footnote 15). Colored light and colored materials are related to each other here: color is reduced to hue plus saturation, and this is equated to wavelengths and amplitudes of spectral color. Color perception is related to the measurement of colored light. This reflects outdated concepts of objectivity.

and Munsell color notations[19] (Fig. 8). The CIE-System underlies all computational color activities, such as color measurement and color mixing.

The published standardized colors in the color atlas serve as references for the comparison with any kind of sample. Hård and Sivik write that "making comparisons with a well-defined standard" will enable "objective" measures of any surface color to be taken. Cautionary notes are added, for instance, that the measured appearance of a color "would only be valid under specific lighting and viewing conditions", and that the color order system is based on processes of physiological color perception, not on the behavior of pigment or light mixtures.[20] Many theoretical questions may be raised at this point (see footnotes 24, 25 and 26 for some). Here, the translation from a reference color in the notation system to a spectral color and back to an industrial formulation of the referenced NCS standard corresponding to the original paint, in theory at least, is the topic.

The limitations to the theory underlying color notation systems

The comparison of the surface to the reference in the color atlas or color index is accompanied by uncertainty: how good is the sample surface, how close is the reference to the sample, how good is the visual observation, how would it be under different conditions of lighting. This is a question of labeling accuracy.

The reference color representing a location on the surface of the NCS color sphere is, in fact, already a materialization of a color. Thus, a substitution of one composition of paint to another has taken place with this act of matching color to reference sample. The implications of this substitution and the other material substitutions that will follow on the way to the new paint are assumed to be negligible. The thought that the effects on space of a blue, for example, depend only on its blueness and on its gloss, and not on its granular structure, surface structure, layer thickness, and pigment chemistry as modified by the binder, underlies this statement of equivalence. It denies the dual nature of color as wave and particle.

In the next step, a notation that specifies a location on a color sphere is substituted for the reference sample. A location on the color sphere as defined by the three numbers chromaticness, whiteness, blackness is substituted for the reference sample in the color atlas or index. Material has become number. These three variables are then translated to a location in the CIE-color space described by the three variables: x, y, and z. Color is regarded as a composite of wavelengths of colored light and their relative amounts. If these wavelengths in the range from 380 to 700 nm align, from reference to system notation to spectral notation and back to a new reference, then the color on the wall and its effects on space will be assumed to be the same. This denies the dual nature of color as a physical aspect of a surface in light and as an act of perception. Color perception, it is argued here, depends predominantly on the wave properties (wavelength and amplitude) of a color. "Effectively, it is the color perception *per se* that has its place in the system", write the originators of NCS.[21] This means that color perception and differentiation have been reduced to a question of spectral location, which is an act of communication. This is a common practice,[22] and it is a fundamental error.

Spectral color theory is based on the premise that three variables are sufficient to differentiate any color.[23] The theory is also applied to material color. It underlies the premises upon which color matching and referencing are performed by NCS. The qualities we assess when we see a color are not, however, limited to the aspect of its blueness, grayness, and saturation, for example; we see more and more happens physically than the simple interaction of an absorbing pigment with light between 380 and 700 nm. Since the range of wavelengths within which we perceive color is not limited to the range of wavelengths within which we perceive colored light, and aspects of color such as density, transparency, and light reflection from crystalline pigments are neglected by the theory, it is such a rough approximation that it can deliver only the most basic information. Establishing a theoretical equivalence between color and light, as well as location and perception, amounts to the disembodiment of color, and it turns perception into an exact science. Neither of these equivalences agrees with modern theories of physics and color perception.

It is ironic to note that the neglect of the material aspects of color and color perception implicit to the color matching and mathematical translation activities described above, all of which were developed to make color communication and color matching more exact, have caused architectural color restoration to become a matter of unknowns and material substitutions. Curiously, color research is firmly mired in color theories that base their interpretations of reality on Newton's optics; color is operated upon in terms of wavelengths only.[24] This delegates the neglected question of color materialization to the companies mixing the new paint. The final translation back to a modern paint made with a mixture of (unspecified) pigments common in industrial paints today produces something colored, but certainly not the material that was once used.

Since color effects on people and on space depend on the materials used to color the space, the color effects in the polychromy will have changed to an undeterminable extent by these procedures of comparison, translation, disembodiment und materialization. We propose that a conclusive treatment of color *must* complement the three determinants specified by NCS if one wishes to identify and restore color in a restoration. In the next section, we introduce a straightforward method for color identification and translation to modern paints very close to the originals in terms of their optical and material qualities.

The reconstruction of the interior polychromy of Villa La Roche

Villa La Roche was constructed by Le Corbusier/Pierre Jeanneret between 1923 and 1926 in Paris. The restoration involved: 1. the definition of the layer to be restored; 2. the chemical and physical analysis of this paint layer; 3. the formulation of a new paint made with the original pigments; 4. the visual adjustment of the historical formulation until it matched the original sample under microscopic conditions; and 5. the formulation of a modern paint optimized in terms of non-toxicity, history and modern conditions of use in the renovated building.

A typical sample was removed from the wall surface, mounted under a light microscope model Keyence VHX and photographed. Microchemical assessments under the light microscope with acids and bases allowed conclusions to be drawn concerning pigments and particularly the binders that were used. Tables compiled by the author listing pigments and their dates of use, restoration reports, and archival material, were consulted to narrow down the choice of pigments to give a "most likely" composition (pigments and binder) for the original paint. A small batch of the paint was produced, and a sample of it compared to the original under the microscope. The formulation was adjusted until the new paint looked identical to the old one. This was submitted to the architects responsible for the restoration, Pierre-Antoine Gatier and Bénédicte Gandini, restorator Ariel Bertrand, and the director of Fondation Le Corbusier, Michel Richard, for approval, or for further adjustment. In some instances, binders that were judged to be too sensitive to the flow of visitors to the Fondation were stabilized by adding synthetic polymer. Lead white and chrome yellow were replaced using modern, ecologically sound pigments, without,

however, altering the paint's granular structure and color appearance.
Tables 1-4 list the findings, including samples, formulations, modern adjustments and comments.

Discussion

Efforts to interpret an architectural polychromy in terms of translations to references in color notation systems are incapable of restoring colors accurately and making spatial effects visible. The premises upon which the color theories of the notation systems are based are too limited. 1. The limitation of the realm within which color appearance is assessed to the realm of wavelengths within which colored light is perceived represents the dematerialization and the disembodiment of color. 2. The assumption that color differentiation can be accounted for by three variables relies on a theory correct for light but incorrect for weakly absorbing, strongly reflecting materials, such as natural pigments. 3. The correlation of spectral color measurements to color perceptions is untenable. It establishes a simple, causal relationship between perception and communication. 4. The consequence of these three errors in thinking, the lack of consideration for coloring materials when assessing color effects in architecture, ignores the single most important determinant for color effects, the pigment, in its context of paint and binder.
Color theory should be expanded to include the dual nature of waves and matter, and the dual nature of color as surface quality and perception. In the meantime, efforts to reproduce meaningful concepts of polychromy in architecture should rely on the identification and the reproduction of coloring materials to make new paints. Interventions based on coloring materials ask for no assumptions that violate the premises of modern physics.
We present an example of one such identification and translation procedure in this publication. The polychromy of Villa La Roche in Paris was restored, paint by paint, to a condition as close as possible to the original, using microscopic methods that avoid the reduction of material appearances to optical descriptors, the effects of damaged surfaces of laid-free paint surfaces, and the translation of materials to references in notation systems. Since color appearance is not limited to the perception of hue, saturation (chromaticness), lightness and blackness, but also includes other aspects such as warmth, texture, apparent weight, transparency, gloss, density, and others, this is a reliable procedure for restoring color, since it considers all of these.
The research presented indicates that pigments, pigment-light interactions, and the granular structure of the paint are important to color appearance and spatial effects in architecture. These variables are not represented by reducing surface appearance to three variables that define a location in a color space. The final color perceived and the spatial effects of a color depend on the following factors. 1. Hue, as a general category. Red enlarges, blue recedes, yellow advances, white attracts attention, and so one. 2. Pigment composition. A sky blue shade recedes strongly and glows in the shade if it is made with ultramarine blue. The same shade of blue made with cobalt blue is more substantial and less elusive. The same shade of blue again made with phthalocyanine blue appears to be more superficial and much greener and flatter under artificial light sources. 3. Gloss and the nature and amount of binder coating the pigment particles. 4. The granular structure of the particles in the paint as they reflect, scatter or absorb light. This includes the layer thickness of the paint and the granulometry. A group of researchers around Milene Gil compare the effects of natural iron oxides and synthetic oxides on colorimetric parameters of lime paints. They conclude that "the surface appearance attributes (ex. paint texture and its opacity/transparency) play a key role in the colorimetric interpretation and in the final colour perceived".[25]

Conclusion

In architecture, *color is a material*. To get color interventions right, the materials must be considered, not simply the spectral locations. We present a practical technique for color identification that allows researchers and renovators to reproduce an architectural polychromy accurately. The intervention technique em-

Table 1

The polychromy of Villa La Roche (1923-1926)

This research was funded by kt.COLOR.

Sample	**Formulations**	**Comments**	**CMYK**
 Sample 1 entrance hall the interior white	1926 Natural chalk paint in hide glue binder (traces were remaining) 2009 Cellulose and PVAC-glue paint, natural pigments	The name is a misnomer, since the paint contained no added ochre. It was made with pure chalk from presumably local sources.	LC 26.073 Sienne naturelle pâle
 Sample 2 port marron interior woodwork	1926 Oil paint pigmented with burnt umber 2009 Modified oil paint, burnt umber	This dark brown oil paint could be removed easily with strong base (KOH). It was used on window frames, doors and other interior woodwork.	LC 26.130 Terre d'ombre brûlée
 Sample 5 blue from back of gallery	1938 Matt paint with ultramarine pigment, binder unknown 2009 Cellulose and PVAC-glue paint, cobalt blue pigments	In 1926, the back of the gallery was painted with a dark umber oil-in-glue emulsion paint. In 1938, it was repainted light blue. A Salubra wallpaper color was used in 2009.	LC 32.032 Bleu ceruleun moyen 2
 Sample 6 ultramarine blue off the entrance hall	1926 Ultramarine blue and bone black in a casein-glue binder 2009 Ultramarine blue and bone black in a cellulose-PVAC-glue emulsion binder	When entering the gallery, it unfolds in front of the viewer like a white sculpture. This effect arises because certain walls were painted dark, like this one, enabling the white to be seen even better.	LC 26.020 Bleu outremer foncé

Table 2

The polychromy of Villa La Roche (1923-1926)

This research was funded by kt.COLOR.

Sample	Formulations	Comments	CMYK
 Sample 7 medium green chambre d'ami	1926 Glue paint with Prussian blue, chrome yellow and white pigment 2009 Cellulose and PVAC-glue paint, inorganic pigments	This color was a surprise since previous renovations resulted in a light, grass-green shade being on the wall. The more gentle, bluer green found under old layers is more stable in the shade.	 LC 26.045 Vert Villa La Roche
 Sample 9 light gray behind the ramp	1926 Glue paint pigmented with chalk and bone black 2009 Cellulose and PVAC-glue paint, natural pigments	Le Corbusier appears to have experimented with the choice of gray for this wall. The oil primer had some pigment in it, the first coat was darker, the second coat of paint slightly lighter.	 LC 26.012 Gris clair La Roche
 Sample 11 bleu Charron narrow passages	1926 Oil-in-glue emulsion paint with Prussian blue and baryte 2009 Cellulose and PVAC-glue paint, inorganic pigments (seen in the foto on the right)	Two surfaces show this grayish blue, both of them on one side of narrow passage ways.	 LC 26.030 Bleu Charron
 Sample ramp in gallery	1926 Oil paint pigmented with burnt Siena 2009 Oil paint pigmented with burnt Siena	A sketch of the gallery exists in which the ramp is painted with vermilion. This is said to have been too dominant for Raoul La Roche, who hung paintings in the gallery.	 LC 26.120 Brun rouge La Roche

Table 3

The polychromy of Villa La Roche (1923-1926)
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Sample	Formulations	Comments	CMYK
 Sample from the radiator in the kitchen	1926 Oil paint with lead white and bone black pigment 2009 Oil paint with zinc white, titanium white and bone black	This radiator was rather rusty but had never been repainted. Cleaning the sample allowed us to reconstruct the oil paint used for metal isntallations in the Villa.	 LC 26.010 Gris foncé La Roche
 Sample 10 gallery upstairs	1926 Oil tempera paint (oil in water emulsion) with burnt umber 2009 Cellulose and PVAC-glue paint with burnt umber	The craftsmen in the 1920s differentiated binders according to pigments. Dark umbers become less sensitive to touch and age beautifully if oil is emulsified into the glue paint as was done here.	 LC 26.130 Terre d'ombre brûlée
 Sample 1 oil paint from handrail	1926 Oil paint pigmented with English green and bone black 2009 Oil paint pigmented with cobalt green and bone black	The sample shows the lead primer (mennige) and the early, almost black green that looks splendid with the brass knobs. Successive renovations made the green become much lighter.	 LC 26.040 Vert noir
 Sample 14 Salle a manger dining room	1926 Oil-in-glue emulsion paint with red ochre and chalk 2009 Cellulose and PVAC-glue paint, natural pigments	No other room changed as much in the course of the renovation as this one. The previous, pink acrylic paint looked unpleasant. The natural pigments and paint grace the space with a gentle glow.	 LC 26.122 Sienne brûlée claire

Table 4

The polychromy of Villa La Roche (1923-1926)

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Sample	Formulations	Comments	CMYK
 Sample 17 white oil paint	1926 Lead white in oil 2009 Titanium white and natural umber in oil	Lead white is in itself a beautiful color. It was widely used, on woodwork and in the kitchen for instance. To approach its beauty without the lead, we use titanium white tinted with natural umber.	LC 43.2 Ivoire
 Sample 18 light gray oil paint	1926 Oil paint with lead white and bone black pigments 2009 Oil paint with titanium white and natural pigments	Le Corbusier preferred to use shadowed colors in dark spaces - they look elegant and stabilize themselves in the shadows. Porcelain white and dark browns accompanied this hue.	LC 26.015 Gris blanc huile
 Sample 8 ochre	1926 Glue paint made with natural ochre 2009 Cellulose and PVAC-glue paint made with natural ochre	This straw-color appeared under white color in the wardrobe off the gallery space. It glows in the half-shade as only natural pigments can do.	LC 26.072 Sienne naturelle claire
 Sample 20 ochre oil paint librabry	1926 Oil paint with lead white and natural siena pigments 2009 Oil paint with zinc white and natural siena pigments	Artists have used Siena to tint oil paints throughout time. The translucency of the natural pigment makes attractive, earthy tones. Other ochres look more fleshy and denser.	KT 09.003 Sahara clair

ployed in the restoration of the interior polychromy of the Villa La Roche was novel in that the original pigments were used in the formulation of the new paints. Samples provided by restorator Ariel Bertrand were analyzed by microchemical and microscopic techniques. The pigment and the binder compositions of the samples were determined. Standard analytical procedures that yield information on the chemical composition of a paint were applied to gather facts and to propose a correct intervention. A reformulation of the paint using the original pigments and binders based on the data available was undertaken. The formulation was adjusted until the new paint showed precisely the same color and layer structure under a light microscope as the original paint layer. In applying the paint, the original application technique with brush-strokes was used by the on-site craftsmen. Errors in color made in previous efforts to maintain the interior polychromy were corrected. The appearance of the Villa La Roche changed dramatically after its polychromy was restored using this method.[26]

This procedure ensures that (1) color appearance, (2) pigment and binder compositions, and (3) paint granular structure, are closely similar to what was used in the original polychromy. These are the factors that describe color and determine the spatial and psychological effects of an architectural polychromy. The expenses for the analyses necessary to identify what was once used in a construction and to translate this into optimal interventions are reasonable. The specifics of pigment-surface-light interactions central to spatial color effects can be reconstructed accurately and the intentions of an architectural polychromy better understood if such a description of color is used in restoration.

Notes

1. A. Hård, L. Sivik, *NCS-Natural Color System: A Swedish Standard for Color Notation*, in "Color Research and Application", 6, 1981, pp. 129-138.
2. A.H. Munsell, *A Color Notation. A Measured Color System, Based on the Three Qualities Hue, Value, and Chroma*, Boston 1905.
3. The hue is the property of colors by which they can be perceived as ranging from red through yellow, green, and blue, as determined by the dominant wavelength of the light. In German: *der Farbton*. Definition from the *American Heritage Dictionary*, retrieved online Feb. 3, 2012.
4. The paint contractor A. Célio listed the pigments to be used in Villa La Roche, asking for confirmation of the order. The list is in the archives of Fondation Le Corbusier under inventory no. H1(3)254. The pigments were yellow ochre, red ochre, ivory black, natural Siena, burnt Siena, natural umber, burnt umber, English green, ultramarine blue, Charron blue (Prussian blue with natural baryte) and chrome yellow.
5. *Natural Color System NCS Index 1750 Original*, Scandinavian Colour Institute, Stockholm 2004.
6. *Baumann Farbtonkarten System Prase*, Paul Baumann Verlag, Aue 1912.
7. P. Ball, *Bright Earth: Art and the Invention of Colour*, Chicago 2003.
8. When light strikes a surface, some wavelengths are absorbed by pigments in the material on the surface. All non-absorbed wavelengths of light are remitted (re-emitted) back into the space, either by the paint if it is opaque, or by the wall behind it, if the paint is transparent. Remitted light can be specular (mirror-like) or scattered (diffuse). The modern pigment industry prefers opaque pigments and ones that scatter light; they are more efficient in terms of hiding power. Their granulometry is regular and the particles small. Traditional artists' pigments, such as natural Siena or ultramarine blue, were more specular, coarser, and their particle distribution was less regular. This gave them a deeper, more luminous appearance.
9. "A house that is completely white looks like a cream jug" (Le Corbusier, 1926, cited in J. de Heer, *The Architectonic Colour*, Rotterdam 2009).
10. M. Wigley, *White Walls, Designer Dresses: The Fashioning of Modern Architecture*, Cambridge MA 2001.
11. Color is a topic that fascinates philosophers, poets and physicists alike. Goethe, Ostwald, Wittgenstein, Heisenberg, Dürr, von Weizsäcker, Schopenhauer and others have turned to the phenomenon and written about it at the ends of their careers. I presume that it is because, with color, poetry and physics, the subjective and the objective, are so intimately linked, that any effort to reduce the phenomenon to one or to the other ultimately fails to satisfy the inquiring mind. Le Corbusier appears to have realized this. His efforts to produce a rational set of rules for the application of color to architecture can be understood as an attempt to control the poetic effects of color, so that they cannot wreak havoc on the volumes and proportions of the construction (W. Heisenberg, *Die Goethesche und die Newtonsche Farbenlehre im Lichte der Modernen Physik*, in "Wandlungen in den Grundlagen der Naturwissenschaft, 6. Auflage, Leipzig 1945; D.L. Sepper, *Goethe contra Newton: Polemics and the Project for a New Science of Color*, Cambridge MA 2003; J. De Heer, *The Architectonic Color* … cit.
12. A. Hård, L. Sivik, *NCS-Natural Color System* … cit.
13. A.H. Munsell, *A Color Notation* … cit., p. 76.
14. The Natural Color System is a proprietary perceptual color model published by the Scandinavian Colour Institute based in Stockholm, Sweden. See http://ncscolour.com for more information.
15. The Swedish natural color system NCS orders colors according to the three values chromaticness, whiteness and blackness. The Munsell color system orders colors according to the three values hue, chroma and lightness. The spectral color space CIE

uses hue, saturation and brightness. All of these color order systems are, in fact based on empirical optical laws formulated by Hermann Günther Graßmann (1809-1877). His laws are a refinement of Newton's optical and Helmholtz's tri-chromatic color vision theories. The first Graßmann law states that each color impression can be described conclusively by three basic optical values such as hue, saturation and value (HSV; *Farbton, Sättigung, Hellwert* in German). Furthermore, human color perception is presumed to be nearly linear, such that the perception of composite hues can be viewed as linear combinations of the perceptual qualities of the components. Although his name is little known, Graßmann's laws are the foundation upon which modern color theories and color order systems are based. For more information, see http://en.wikipedia.org/wiki/CIE_1931_color_space#Grassmann.27s_law and http://de.wikipedia.org/wiki/Graßmannsche_Gesetze (Downloaded January 29, 2012).
16. F.W. Billmeyer Jr., A.K. Bencuya, *Interrelation of the Natural Color System and the Munsell Color Order System*, in "Color Research and Application", 12, 1987, pp. 243-255.
17. A. Hård, L. Sivik, *A Theory of Colors in Combination-A Descriptive Model Related to the NCS Color-Order System*, in "Color Research and Application", 26, 2001, pp. 7-9.
18. A. Hård, L. Sivik, *NCS-Natural Color System* … cit.
19. N. Ohta, A.R. Robertson, *Evolution of CIE Standard Colorimetric System*, in "Colorimetry: Fundamentals and Applications", John Wiley & Sons, 2005, pp. 175-228. The theories used to assess and program additive (spectral color) mixing are applied to subtractive (pigmented color and dyes) mixing using complicated algorithms, usually the modified Kubelka-Monk model (see p. 183). The Kubelka-Monk model assumes that light scattering is much stronger than light absorption and that light reflectance from the paint surface is negligible. Natural pigments as they were used in architecture before 1920 are weakly absorbing pigments and they contain crude crystalline particles that are highly reflective. Pigments such as natural Siena, lapislazuli, and calcite (crystalline calcium carbonate) show poor correspondence to the colorimetric operations used by current assessment and formulation software.
20. A. Hård, L. Sivik, *NCS-Natural Color System* … cit., p. 129.
21. Ibidem.
22. J. Gage, *Colour and Meaning. Art, Science and Symbolism*, London 1999, p. 29.
23. Johann Wolfgang von Goethe was one of the first to resist this oversimplification. His arguments were wrong, his conviction that color as a perceptual phenomenon cannot be described conclusively by adding and subtracting wavelengths of light is fundamentally correct. Goethe appears to have realized that object and subject, or the color on the wall, and how it affects light and space to the one viewing it, cannot be separated, and an exact science of numerical operations made of the physical phenomenon. German readers interested in this will find Carl-Friedrich von Weizsäcker's comments interesting (C.F. von Weizsäcker, *Zeit und Wissen*, München 1992).
24. Recent research indicates that the opponent theory of color vision should be replaced by a complementary theory of color vision which accounts for the opponent theory and the tri-chromatic theory of Young and Helmholtz. Claims that NCS describes the process of color vision are incorrect; the opponent theory of color vision and NCS describe hue appearance and not the physiology of color vision. The complementary theory of color vision has been called the most far-reaching theory of color vision to date (R.W. Pridmore, *Complementary Colors Theory of Color Vision: Physiology, Color mixture, Color Constancy and Color Perception*, in "Color Research and Application", 36, 2011, pp. 394-412).
25. M. Gil, J. Aguiar et al., *Colour Essays: An Inside Look into Alentejo Traditional Limewash Paintings and Coloured Lime Mortars*, in "Color Research and Application", 36, 2011, pp. 61-71.
26. T. Benton, *Villa La Rocca: Revisiting the Villa La Roche*, AD-AGP_FLC Publication, 2009, 2049_3390. http://www.fondationlecorbusier.fr/CorbuCache/2049_3390.pdf, p. 23.

Biography

Born in 1962 in Germany and raised in the United States, Katrin Trautwein studied Organic Chemistry at Johns Hopkins University in Maryland. She obtained her doctorate from the Swiss Federal Institute of Technology (ETH) in Switzerland. After working as the head of product development for a small manufacturer of artists' paints, she founded kt.COLOR in 1998. A period of intense collaboration with artists, architects and conservators followed, in which it became clear that questions of architectural color are best resolved by connecting scientific empirical knowledge to cultural mores and traditions evident in art and documented in the literature on the history of art. This integrative approach to color as a rational science rooted in artistic tradition yields stratling answers to modern ecological and aesthetic demands as voiced by architects and conservators. Scientific assessment methods developed by kt.COLOR stretch beyond the comparision to NCS color codes to include questions of pigment structure, light reflectance and paint application. This scientific approach to questions of aesthetics has made her a much requested speaker and consultant to architects, students, conservators, and designers.