# INTERACTIVE COLOR THEORY - EDUCATION, RESEARCH, AND PRACTICE: The Development of CoMoS3

R. Peter Wilcox, Asst. Prof.
Department of Architecture
University of Oregon
Eugene, OR 97405

"...even a little thought reveals the major, if often subconscious, role that colour plays in our assessment of the quality of life." (Chamberlin & Chamberlin, 1980)

## ABSTRACT

This paper describes one way to integrate the computer into architectural color research, teaching, and practice. In my work with the Architecture and Interior Architecture programs at the University of Oregon, I am currently developing software exploiting the full three-dimensional and dynamic nature of the Munsell color organization, thereby making it easier for students to learn and apply color theory. CoMoS3 provides an interactive means of understanding and exploring color relationships from within the Munsell system of organization, employing the Munsell harmonies essentially as both a theoretical datum and an interactive "mentor" for color studies. In describing CoMoS3, Color Modelling System in 3D, this paper proposes a method for the integration of computers into one of the more creative and subjective aspects of architectural education and practice. The paper also discusses the problems inherent in this approach and suggests directions for future work.

## COLOR AND COMPUTING

The psychophysical perception of the special quality of light known as color - occurring at the receptors of the retina and deep within the mind - retains much of its mystery even after over 300 years of scientific inquiry (Judd and Wyszecki, 1975). The nature of color, inseparable from its sensible and mental perception, has been a problem of continuing interest since ancient days. Physicists and philosophers, from Newton and Goethe to Schroedinger, artists such as Claude Lorraine, Matisse, and Van Gogh, and architects like Le Corbusier, Barragan, and Alexander, have continued to find evidence of profundity within color, yet it is "first and foremost an experience."(Keuhni, 1983)

Reinforcing the qualitative nature of color is the fact that, in spite of a substantial accumulation of knowledge about color interaction, the design of harmonious color arrangements remains primarily an intuitive rather than a structured or scientific pursuit. Hopefully, by applying the computer to this creative and subjective field, two complementary, positive effects will result for the users of color space modelling software such as CoMoS3: 1) color will be better understood and enhanced through a more sophisticated means of study, and 2) the computer will be better understood as a tool capable of supporting creative expression and humanistic architecture. (Wagter, 1986)

The ability to see individual colors and to build color relationships within a three-dimensional structure is implicit in virtually all the various color organizations, or spaces. The problems of discontinuity, simultaneous color contrast, and adaptation effects all but preclude the full and natural utilization of color spaces by manual (i.e. two-dimensional) methods. Given an effective visual illusion of depth and the ability to select or change colors instantaneously, the requirements of three-dimensional color interaction are entirely viable. These abilities are readily provided by computer workstations with multiple bit-plane analog displays.

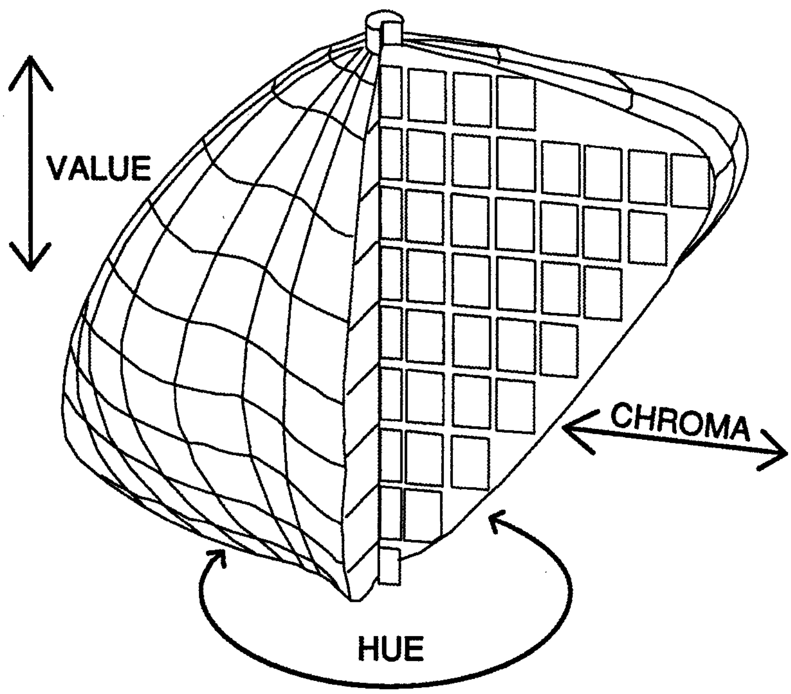


Figure 1. MUNSELL COLOR SOLID
(adapted by author from Chamberlin & Chamberlin, 1980.
Courtesy of Wiley & Sons, Inc.)

## THE MUNSELL COLOR THEORY: 3D AND HARMONY

The Munsell color system is based on empirical studies conducted by Albert Munsell near the turn of the century. These involved over 20,000 separate color matching experiments. Munsell's work, first published in 1905 and revised and extended in the early 1940's (Newhall, Nickerson, & Judd, 1943), has provided a basic and practical color organization system widely employed in architecture and interior design, particularly in the English-speaking world.

The Munsell system is based on a three-dimensional - hue, value, and chroma - color space currently containing over 1600 separate and perceptually uniformly-spaced colors [ 1 ]. In the illustration above, hue, the named color based on wavelength, can be seen to encircle the central axis of the space. In the Munsell system there are five principle and five intermediate hues plus up to ten subdivisions of each. Chroma, the measure of purity of a hue, is measured by the radial distance from the central axis. The axis itself is a neutral gray scale with black at the bottom, white at the top, and nine intermediate intervals indicating ascending levels of value, the measure of brightness of a color. Munsell himself felt that a two-dimensional color diagram was "as incomplete as a map of Switzerland with the mountains left out" (Munsell, 1905). Nonetheless, the Munsell system is typically learned and employed by using the large, two-volume set of the Munsell Book of Color. Furthermore, this two-dimensional, fragmentary version of the full manifestation of the Munsell color system may be the principal reason for the relative obscurity of the Munsell harmonic theory - since the theory is fully-embedded in the three-dimensionality of the color space. In addition, some of Munsell's harmonies are actually dynamic in their truest nature. For example, the "elliptical path" harmonies, which derive from Munsell's observations of changing sky colors at dusk or dawn, are best understood in a sequence of evolving coloration. Clearly, significant portions of Munsell's work can be accurately perceived and evaluated only with a medium capable of interactive, three-dimensional, animated color.

Munsell theorized six fundamental harmony arrangements. Most of these arrangements are founded on notions of a "balancing" of chroma and/or value about the neutral gray axis, and especially about the middle gray - so-called value 5. Palettes are balanced by an inverse proportioning of the color areas. The proposed harmonies include four types of complements, four types of monochromatics (single hue), two types of analogous, two types of split complements, two types of so-called elliptical paths, and ascending/descending color sequences.

Several different attempts have been made over the last 90 or so years to satisfactorily represent the three-dimensional Munsell color space, and thereby to achieve the fullest utility of its concepts. Munsell himself began with a quite literal three-dimensional color "tree" in 1898. More recently, the system has been displayed on computer monitors in primarily two-dimensional, orthagonal, and therefore partial, views. One exception is the work of Gary Meyer, under the guidance of Donald Greenberg, at the Cornell Computer Graphics Program. Meyer's work resulted in a program capable of displaying various sections through the Munsell space - similarly to CoMoS3 - and a three-dimensional model as well. Meyer's software was focused primarily on instructing computer graphics students in the fundamentals of color science and not with any application in architecture or design education. In my estimation, the most important contributions of Meyer's work thus far have been in the description and solution of many of the complex problems of accurately displaying color on VDU's (Meyer & Greenberg, 1980). I am very fortunate in having Meyer serve as a consultant in my work; he is assisting in the development and implemention of CoMoS3's innovative monitor calibration routines. Other contemporary building modelling systems typically employ a staged, two-dimensional process for color selection. For example, in the McDonnell-Douglas GDS

"Solid-Color-Shading" system or in Skidmore-Owens-Merrill's DRAF system [ 2 ], one selects colors in a sequential manner by dealing with one "dimension" of color at a time.

CoMoS3

The intended capabilities of CoMoS3, as established at the onset of the project, are the following:

0. INTUITIVE, REAL-TIME USER INTERFACE. The software itself must remain fully transparent - not itself becoming the primary object of the computer exercise. The three-dimensional spatial relationships inherent in the color space must be obvious. Palette generation must be easily mastered. Finally, the program must operate as closely as possible to real-time so that the transitory affects of manual methods of color selection are avoided and the intuitive nature of interaction within the three-dimensional color space is enhanced.

1. GENERATION OF PALETTES FROM MUNSELL "RULES". The user may invoke a menu of Munsell harmonies, together with their related variables. As an example, given a single, chosen hue, a complex set of alternate, harmonic palettes is quickly generated and compared.

2. PARAMETRIC VARIATION OF COLOR PALETTES. Student researchers or designers may transform a color or a palette by parametrically varying hue, value, or chroma. The relative effects of each of the dimensions of color is thereby assessed along with the qualitative differences of the varied palettes themselves.

3. DYNAMIC CONSTRUCTION AND EVALUATION OF PALETTES AND ADDITIVE COLOR EFFECTS. Users may construct palettes independently or in parallel with a Munsell harmony. Additionally, researchers or designers may study sequential or additive perception of color by describing varying paths, which are fundamental to the Munsell system, through the color space.

4. COMPARATIVE ANALYSIS OF CONTEXTUAL OR PROPOSED PALETTES WITH MUNSELL STRUCTURED HARMONIES. From a recorded palette predominating within a region or existing in a historic structure, a user may analyze the harmonic structure as revealed by Munsell's color space and harmony theory. The user may also discern characteristic anomalies or construct related color ranges. Similarly, users may analyze their own color proposal for structural patterns and relationships by matching them against Munsell's.

5. PALETTE MAPPING INTEGRATED WITH ARCHITECTURAL DRAWINGS. Users may interactively test color schemes in the context of CADD drawings of buildings or spaces. Similarly, parametric variation of individual colors or of entire color schemes may be accomplished while viewing architectural drawings.

in its current form, my software is intended in part for use in color theory subject area classes. At the UO, these classes are taken by many architecture students and all interior architecture students. Later in this paper I will describe a plan to integrate the software with CADD (number 5 above) to facilitate its use in the architectural design studio.

In a very general sense, CoMoS3 treats the Munsell harmonies as the "expert" in an knowledge-based expert system. The Munsell harmonies guide students or researchers in the discovery and creation of color relationships which may be seen to partake of a theorized objective beauty. CoMoS3 encourages color experimentation and employment by providing guidance with a readily accessible, but non-confining, structure. Complex color palettes or harmonies can be quickly created and compared to each other or to Munsell's proposed harmonies, and/or viewed within the Munsell three-dimensional color space. These functions allow the generation of palettes meeting specific criteria, in such diverse applications as establishing perceptually-balanced coding for electron microscope images or graphic design, as well as the refinement of color intuition or for actual application in architecture. Although it remains a somewhat awkward task at the present time, palettes created by master colorists, for example, or color ranges found in nature, can be analyzed and their operant principles or intentional deviations from Munsell's theoretical norms uncovered. Parametric variations of palettes can be immediately generated to compare the qualities inherent in harmonies based on differing hues, values, or chromas. And, at the same time users avoid the interactive effects of manual color selection methods which up to this time have interferred with this type of color study.

## PROBLEMS OF SOFTWARE DESIGN

At the heart of the program's pedagogic utility is, of course, the user-interface. The program relies on pull down menus, context-sensitive help screens, and a novel, animated color selector requiring localized movements of a mouse or a stylus for all selections.

The realization of a functional three-dimensionality to the color space was considered to be of the utmost importance, therefore I have given a great deal of attention to the manner of displaying the color "chips" on the screen in the 3D mode. I rejected prismatic solids even though these most accurately represent the analog character of the color space because conveying their shape requires either shading or outlining. Either of these techniques would compromise color comparison and selection. The chips are therefore essentially two-dimensional themselves - single curved surfaces perpendicular to radii - displayed within a three-dimensional space. Perspective viewing of the color space has been implemented experimentally at this time. My initial hardware, the Vextrix computer and color display, has very fast perspective routines in ROM which make this mode of viewing an attractive option in terms of interaction. However there is a trade-off due to the foreshortening of colors which are perceptually deeper into the color space. I plan to implement an isometric view through a transparent, wireframe solid on our new 32-bit machines, Macintosh II's, on a trial basis. The color space spins easily about its own axis and tilts variably so as to minimize overlay masking and allow the best viewing angles. Both sectional views - hue "sections" and value "plans" - and the cylindrical views - chroma "scores" - automatically assume the main viewport position either when appropriate to the current harmony-type or whenever the user desires. Sectional and cylindrical views are not simultaneously visible on the screen during 3d viewing, although I hope to implement this capability later.

An important goal of the software is harmony recognition and comparison. I am working to establish a set of routines that will analyze a new or an existing color scheme. By having the software find the closest Munsell harmony, the program establishes a theoretical touchstone for the researcher. For example, a palette of four given colors by definition could not be either a complementary or split-complementary scheme. The program next checks to see if the palette is monochromatic or is composed of analagous, or nearly analagous, hues. Then, the program checks for a descending or ascending sequence, and finally, for an elliptical path. Once found, the closest Munsell harmony(s) is displayed either just below the palette of interest or concurrently if in 3D view mode. The user can then see exactly where there are differences from the "ideal" and can parametrically vary any of the original palettes colors' hue, value, chroma, or area to track the effects on the color interaction. When this "Comparison" aspect of the program is fully implemented I anticipate analyzing the color schemes of reknowned environmental colorists in order to see specifically how they digress from structured harmonies, thereby gaining a clearer understanding of their approach.

I am also working to implement a procedure which allows a series of proposed color schemes to be mapped onto building images created with an independent CADD system, thereby integrating color selection and building modelling (see Norman, 1985). Only when this is completed will the program become a true architectural application. My intention is to allow palette modification and transformation concurrently with viewing the building image. One idea is to have the CADD system and CoMoS3 running in separate, linked windows on the display. Another approach to this problem is importing the building images in IGES, PICT, or another standard format.

The targeted computer for the Munsell software, the Macintosh II, is economically available only with an eight bit-plane monitor. However, displays with fewer than nine bit-planes create a problem when displaying certain views of the color space, i.e. chroma "scores" at low chromas and value "plans" at mid-values, where there are more than 256 simultaneous colors required. Exactly nine bit-planes allow any section to be taken through the color space with all colors displayed. A monitor with more than nine bit-planes, and hence a larger number of simultaneous colors, would be advantageous only from the standpoint of allowing the full Munsell spectrum of approximately 1600 colors to be on the screen at once - not a critical advantage in my opinion. Thus far the only adequate solution to the problem of too few bit-planes I have found is to enhance the display to at least nine bit-planes at the earliest possible moment. In the meantime, I am incorporating a selection algorithm that will reduce the number of hues displayed on the screen by one-half in unutilized segments of the color space whenever there is a shortage of available screen colors. This seems to occur infreqently but nonetheless remains a serious shortcoming. To my knowledge, the greatest current factor limiting the integration of color into architectural education, research, and practice is display and video board cost.

## MONITORS AND THEIR CALIBRATION

Color matching between luminous sources and reflective sources is an extremely complex and unsolved issue on its own. A problem analagous to matching screen colors in CoMoS3 with environmental color is achieving accurate hardcopy output from computer displays in general, a problem undergoing a substantial amount of current research.

The VDU's capabilities and its calibration are critical aspects of the operation of software concerned with the use of color. The necessity of calibration is not limited to a shift to a different brand or model of monitor, but from each individual device to another of the same type. All monitors vary enough for individual calibration to be essential. Even a change in lighting conditions during a given session can, at times, mandate a recalibration.

Another aspect of the number of bit-planes is the effect on color accuracy. My initial monitor (the Vextrix/Electrohome) has nine bit-planes [ 3 ] and is therefore capable of simultaneously displaying 512 colors out of a palette of approximately 16.7 million. This gives a theoretical maximum inaccuracy for an individual Munsell color of about 1/200th of a percent (0.005%). Such a variation is almost certainly not perceptually significant since human beings are typically capable of discerning only about 350,000 total colors (Foley & Van Dam, 1982). Indeed, other factors, such as the difficulties of the match between architectural (subtractive) and VDU (additive) color and varying lighting and surface reflectance conditions present much more important obstacles to design precision. I have no illusions of exactly matching environmental colors - most of which are subtractive pigments rather than additive colored light anyway. The CoMoS3 colors appear to be acceptably close to the Munsell and environmental colors and are accurately proportionate to the Munsell intervals. The greatest single factor of variability in color fidelity on a color monitor is the contrast effect with an inaccurate background color on the screen.

Typically, in order to accurately calibrate a monitor, one must have sophisticated and expensive photometric equipment. An alternative method involves knowing the chromaticity coordinates of the individual monitor's phosphors and making careful measurements of the maximum luminances of the red, green, and blue guns. One then proceeds through a complicated series of linear transformations and matrix equations to balance the color space RGB values with the electron guns and phosphors of the monitor (see Meyer and Greenberg, 1980). The advantage of this calculation-intensive method is that it requires only a relatively inexpensive photometer. I am working with Gary Meyer to create a two-tiered calibration scheme which may eventually be incorporated into the program. Several significant technical problems remain to be solved with this method. When implemented, this method will assist the user in quickly achieving an approximate color balance. Under the program's direction, the user will subjectively match a number of screen hues with provided Munsell color chips. The program will then complete the calibration process. In the meantime, and for more exacting situations, the program will guide the user through the RGB luminance calibration process described above and perform the necessary calculations once readily acquired information is supplied.

## DIRECTIONS FOR FUTURE ENHANCEMENTS

The first enhancement I plan to implement will be video capture software and hardware for acquisition of color palettes from existing rooms, buildings, districts, etc. These captured palettes may then be analyzed by the knowledge-based expert system portion of program, displayed appropriately within the color space, and used as the structured-basis for contextually-harmonic color additions. Currently I can accomplish this process only through manual color matching. Major obstacles remain, especially with regard to calibration and appropriate filtering of lighting effects.

Finally, I would like to enhance the artificial intelligence aspects of the program. At this time I imagine a true knowledge-based expert system which catagorizes and evaluates color palettes in terms of the full CIE color space and analyses harmonies through more than one color theory. Similarly, the program might begin to generate palatte possibilities which meet specified user-input parameters such as desired color interaction, lighting qualities, and palette character effects.

## CONCLUSIONS

The three-dimensional graphic and realtime interactive capabilities of the computer appear to allow a more thorough exploration of certain aspects of architectural design theory. Furthermore, the computer may encourage richer design processes which are in some ways more analogous to the actual sensations of human visual experience than traditional means have made possible, e.g. our mental "space" tends toward a colorful three-dimensionality. Modeling perceptual experience during the process of design, as in sequentially representing color change with changing daylight, raises intriguing questions about the relationship of the designer's creative processes and users' experiential images, to wit: Can the diverse experinces of the designer and the user meaningfully converge? Thus, research into color relationships and design, due to its distinctly experiential basis, provides the opportunity of exploring the links between design media and process, mental imagery, and the experience of architecture. For, as John Ruskin said, "...everything that you can see in the world around you, presents itself to your eyes only as an arrangement of patches of different colors variously shaded" (Ruskin, 1857).

## ACKNOWLEDGEMENTS

My sincere thanks to the School of Architecture and Allied Arts and the Department of Architecture at the University of Oregon for hardware and facilities, a partial leave, and monetary support. Also, I am grateful to the L.L Stewart Fund for a timely grant. The bulk of my thanks go to my superb student programmer, Rick Reed, and to my colleagues, Gary Meyer, for his invaluable knowledge and assistance, David Hulse for the use of his colorful Vextrix monitors, and Art Hawn and Michael Utsey for their helpful advice.

## REFERENCES

Chamberlin, G.J. and Chamberlin, D.G., Colour: Its Measurement, Computation and Application, London: Heyden, 1980, p. ix.

Foley, J.D. and Van Dam, A., Fundamentals of Interactive Computer Graphics, Reading, MA: Addison-Wesley, 1982, p. 606.

Judd, D.B. & Wyszecki, G., Color in Business, Science, and Industry, New York: John Wiley & Sons, 1975. A full explanation of color vision has yet to be formulated. As Judd and Wyszecki note in their canonical work on color, "The complexity of color vision and the seemingly insurmountable difficulties in experimenting with the human eye and brain have so far prevented the development of a comprehensive and satisfactory theory.

Kuehni, R., Color: Essence and Logic, New York: Van Nostrand Reinhold, 1983, p. 1.

Meyer, G. & Greenberg, D., "Perceptual Color Spaces for Computer Graphics", in Computer Graphics, Vol. 14, No. 3, July 1980.

Munsell, A.E.O., A Color Notation, Boston: Ellis, 1905, p. 18.

Newhall, S.M., Nickerson, D. and Judd, D.B., "Final Report of the OSA Subcommittee on the Spacing of the Munsell Colors", Journal of the Optical Society of America, Vol. 33, pp. 385, July 1943.

Norman, R.B., "Electronic Color in the Design Studio", ACADIA Workshop '85 Proceedings, pp. 35-42 contains a good discussion of this kind of color integration and is an excellent introduction to color instruction on the computer generally.

Ruskin, "The Elements of Drawing", 1857. Cited in R.L. Herbert, ed., The Art of Criticism of John Ruskin, Garden City: Anchor Books, 1964, p.2; cf.

Wagter, H. "Stimulating Creativity by Using [the] Computer", ACADIA Workshop '86 Proceedings, pp. 149-153.

## NOTES

(1) Munsell's color space principally differs from other color organizations, such as the similar HLS system so often employed in color models for computer graphics, in that the color spacing is based on perceptual intervals. On the other hand, the HLS system employed by Tektronix and based on the Otswald color space, is formulated through color mixing experiments employing optical instruments to achieve consistent wavelength intervals. Yet, the magnitude of perceptible change in color is far from even across the visible spectrum. The importance of this distinction should be obvious to environmental designers.

(2) Hue, Lightness, or Saturation (HLS), for example, in the case of DRAF, or Hue, Value, or Chroma in the case of the Munsell system.

(3) The Vextrix/Electrohome monitor has the additional, and unusual, advantage of having the exact color temperature of daylight.