MUNSELL COLOR SCIENCE LABORATORY

ANNUAL REPORT
1987

Rochester Institute of Technology

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The Year in Review

This past year has been, perhaps, the most dynamic year since the laboratory's inauguration in 1984.

I am extremely happy to report that the Franc Grum Memorial Scholarship has received sufficient support to become endowed, insuring perpetual recognition of Professor Grum's great contribution to the Laboratory, RIT, and the field of color science . Significant contributions were received from Mrs. Albina Grum and the Eastman Kodak Company. Their support is sincerely appreciated by the entire RIT and color communities.

Mr. Mark Fairchild, one of our top former students, was permanently hired as an Instructor. Mark performed his Master's research under Professor Grum's direction in the area of spectroradiometry of flash sources and the determination of their ocular exposure levels. Mark's current responsibilities include developing our Laboratory's optical instrumentation and teaching coursework in colorimetry, standardization of optical radiation, and vision and psychophysics. Mark is also pursuing a doctoral degree in visual science from the University of Rochester. Laboratory expertise in this area is critical and we are pleased to support his educational efforts.

Several research projects have begun which dramatically enhance our total program. Mr. Fairchild has initiated the construction of a laser visual colorimeter to measure color matching functions. This instrument is aiding students in gaining an in depth understanding of the development of trichromatic theory and the CIE colorimetric system. The instrument will also be a valuable research tool in exploring such areas as observer metamerism, parameters affecting color discrimination, and temporal factors influencing color matching functions. Research in these areas will address fundamental concerns of the validity of colorimetry in describing chromatic stimuli generated on self-luminous displays.

Our research in colorimetrically calibrating CRTs for use in color appearance experiments is nearing completion. A dedicated research laboratory housing our full-color image processor has been modified for this important research area. The system is also being utilized in our coursework where students are performing laboratories to address the transfer function between soft copy and hard copy devices.

Financially, 1987 was a successful year. We received approximately $100,000 in instrument gifts, instrument indefinite loans, and unrestricted grants. This support has enabled us to support much of our research efforts, our students, the initiation of a standardization program, and to insure our academic and industrial education is relevant to the color measuring community. We have received approximately $70,000 in restricted applied research grants during the period covering this annual report. To improve dissemination of information, we have begun to write Munsell Color Science Laboratory Technical Reports describing our research and results in more detail than is possible in journal articles and conference proceedings.

One of the Laboratory's main objectives is to establish a sound standardization program and provide materials and calibrations where these services are either void or difficult to obtain. We have been steadily making progress in this area. A separate facility has been isolated from the main laboratory to house transfer spectrophotometers and our reference spectrophotometer which is under construction. We are currently providing 45/0 calibration services, calibrated white reference material, and contract measurement services.

The Munsell Color Science Laboratory is situated in the College of Graphic Arts and Photography, one of eight colleges within RIT. The Laboratory, when established, was under the academic "umbrella" of the School for Photographic Arts and Sciences. During 1987, the Laboratory has become an integral part of the Center for Imaging Science. This integration has tremendously expanded resources and services available to the Laboratory. The Center for Imaging Science has been identified as the Institute's present and future "strategic thrust." Construction will soon begin on a 72,000 square foot facility to house the Center. The Munsell Color Science Laboratory will have dedicated space for high-accuracy measurements of optical radiation, visual psychophysics, and visual colorimetry in addition to a main laboratory. A doctoral degree in imaging science is under development. When promulgated, research projects of a longer duration may me initiated than currently possible. This program will be unique promising a tremendous resource to the industrial community. RIT's global commitment and orientation to applied research will provide an excellent framework for the doctoral program. We are very excited to be a part of the Center for Imaging Science.

Our industrial short courses have been very well received. The Laboratory is currently offering *COLORIMETRY: An intensive short course for scientists and engineers*. The course stresses the development of CIE colorimetry, its application in quality assurance, and the total uncertainty associated with this application. The course is normally presented twice during the year. This past year, demand was so high a third course was given in late fall.

We are looking forward to a productive year in 1988. We are extremely enthusiastic about our current projects.

The activities I have described would not have been possible without the support of the faculty and administration of RIT, our generous industrial supporters, our colleagues from around the globe, our students, and our advisory board. Thank you all!

Roy S. Berns, Ph.D.
R. S. Hunter Professor
Director, Munsell Color Science Laboratory

January 9, 1988

Research and Development

The students and faculty of the Munsell Color Science Laboratory are involved in a variety of research programs. These programs fall within the framework of the Laboratory's long-standing objectives of performing applied research and development applicable to current industrial needs. Periodically, we initiate small research projects which are fundamental in nature; these projects are primarily educational for our students and faculty. Often, these projects lead to further applied research. An example is our research on uniform color scales. This project will enhance our computer graphics capabilities, psychophysical experimentation capabilities, and add to our understanding of the human factors of manipulating the color appearance of computer generated images.

Visual Colorimetry

Sponsor: New York State Center for Advanced Optical Technology

The main purpose of color science is to study the way in which humans perceive color. This involves many disciplines including physics, chemistry, physiology, and psychology. One of the fundamental areas in the study of colorimetry is the psychophysical study of color vision. The Munsell Color Science Laboratory is dedicated to the psychophysics of color as well as the physics and chemistry of color. To this end, the laboratory has initiated a long-term project in the area of visual colorimetry.

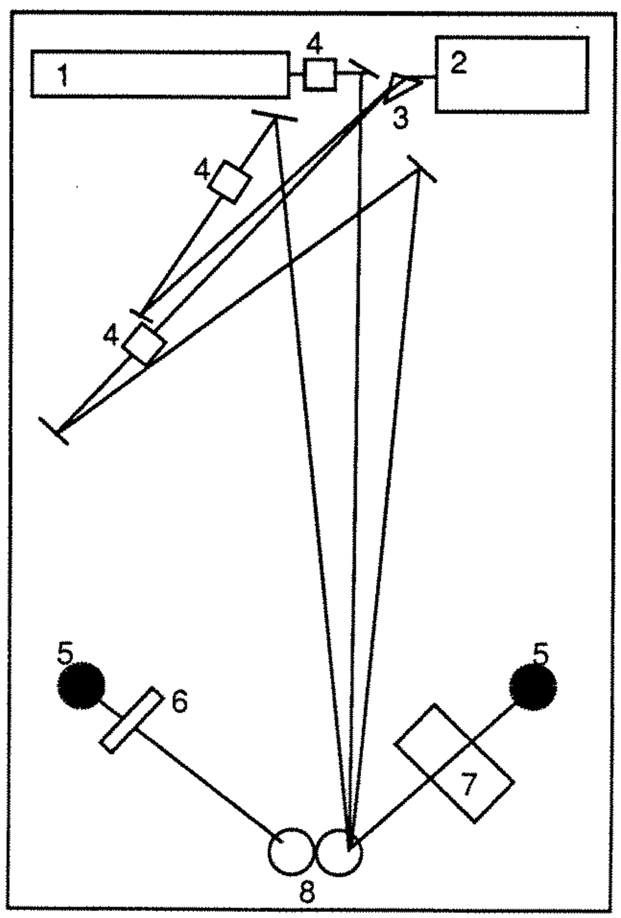
During the past year, Mr. Mark Fairchild of the Munsell Color Science Laboratory has been involved in the design and construction of a visual colorimeter to be used for various color matching experiments. Several basic features make this instrument unique in the world of visual colorimetry. This instrument has been designed to allow the observers to view the matching field binocularly and without head restraints. To accommodate this design, the viewing field must be some sort of a diffuser. In order to have a diffuse viewing field and retain sufficiently high levels of illumination, it was decided to employ lasers as the primary light sources. The use of lasers provides a high level of easy-to-control and stable monochromatic light. In addition, the Munsell Color Science

Laboratory (MCSL) Visual Laser Colorimeter employs the Maxwell method of color matching. The Maxwell method derives color matching functions from matches of an achromatic stimulus with mixtures of various wavelengths of the spectrum and the three instrumental primaries. A final feature of this instrument is that it will be possible to perform color matching with complex fields to investigate surround effects.

A preliminary version of the MCSL Visual Colorimeter was completed in the fall of 1987. Observer's were asked to match an achromatic stimulus (5000K daylight simulator in a dark surround) using a monochromatic stimulus and the three laser primaries. The monochromatic stimulus was varied from 400-700nm in 10nm increments. At each wavelength, the monochromatic stimulus was kept constant and the achromatic stimulus was matched by adding various amounts of the three laser primaries. Preliminary results from the instrument were somewhat disappointing. Proper color matching functions were determined for several observers, however there was a serious signal-to-noise problem. The variable monochromatic stimuli were produced with a 250 Watt xenon lamp and a grating monochromator. When this light was diffused to be mixed with the laser primaries, and viewed, the luminance was significantly lower than what could be produced with the laser primaries. This resulted in very little of the variation in the matches being a function of the monochromatic wavelengths. Since color matching functions represent the variation in an observer's visual sensitivities as a function of wavelength and very little of this variation was measured, the preliminary experiments were more useful as measures of observer precision rather than color matching functions. An additional problem with the preliminary instrumental design was that the 250 Watt xenon source was not stable enough for these measurements and produced an additional source of noise.

The results of the preliminary experiments have led to the rethinking of both the instrumental design and the experimental approach. Three areas for improvement became immediately evident. More monochromatic flux was needed to achieve the desired levels of illumination, a more stable light source was needed to provide the monochromatic flux, and more replicate observations were needed. It was decided that the combination of a tungsten light source and interference filters could provide the increased monochromatic flux and lamp stability which was required. However, this added the physical problem of easily interchanging 31 interference filters to provide all of the wavelengths. This led to the development of a method for determining color matching functions which would rely on significantly fewer wavelengths. Reducing the number of wavelengths also reduces the number of observer matches required and allows for the desired increase in replicate matches.

Although it was desired to be able to replicate some of the earliest experiments in colorimetry, there is no reason to overlook the years of research which have been completed in this area. It is known that the color matching functions of an observer are linear transforms of the cone absorption spectra. The cone absorption spectra have been determined quite accurately by several investigators using several different techniques. Also, it has been shown that most of the variation between normal color observers is due to differences in the levels of absorption in the lens and macula. Therefore, color matching functions could be described as a linear combination of the cone absorption spectra multiplied by the spectral absorption of the lens and macula. A model has been developed which allows the determination of color matching functions based on 5 color matches; one corresponding to each of the cone types, one for the macular pigment, and one for the lens absorption.



1- HeNe Laser
2- Argon Ion Laser
3- Prism
4- Acousto-Optic Modulators
5- Tungsten Sources
6- Filter
7- Filter Wheel
8- Viewing Field

On the preceding page is a schematic optical diagram of the MCSL Visual colorimeter as it is currently being constructed. It consists of a 633nm helium-neon laser for the red primary, a multiline argon-ion laser for the blue (488nm) and green (514nm) primaries, acousto-optic modulators to control laser intensity, two tungsten lamps, a filter wheel with 5 interference filters (420, 440, 460, 540, 570nm), a custom-built diffusing field, and a dedicated personal computer.

The construction of this instrument should be completed early in 1988 and some preliminary results should be reported by mid-year. Some areas which will be investigated with the MCSL Visual Colorimeter are: differences between 2-degree and 10-degree matching; observer metamerism; and adaptation and surround effects.

Spectrophotometric Standardization

Sponsor: The Munsell Color Science Laboratory

The Munsell Laboratory is dedicated to achieving the highest level of excellence in spectrophotometry for colorimetric purposes. To achieve and maintain this goal, a strong standardization program has been implemented.

An important service the laboratory provides for industry consists of contract measurements. The laboratory is often contracted to make spectrophotometric measurements for various industrial purposes. These contract measurements have continued to be provided and, in fact, are in quite high demand. It is important for industry to have an independent, reliable source of accurate spectrophotometric data at a reasonable cost. The laboratory dedicates the income from these measurements to instrumental upkeep as well as the employment of an undergraduate student research assistant who performs much of the routine work.

At the standardization level, a project has recently been completed (Berns and Petersen) involving the mathematical correction of measured spectrophotometric data. The technique was first published by Alan Robertson and then modified by Berns and Petersen. It involves measuring a calibrated standard and performing a multiple linear regression on the differences between the measured and actual values. The regression coefficients can then be used to diagnose and correct the measured spectrophotometric data to match the standard data. This technique has been performed successfully on several instruments with the resulting corrected data being within the NBS uncertainty for the calibrated tiles.

Three instruments in the laboratory have been designated for use in the spectrophotometric standardization program. These are a Milton Roy ColorScan/45, a Milton Roy MatchScan II and the MCSL Goniospectrophotometer. The Milton Roy instruments were chosen based on their flexible and adjustable design and operating characteristics.

The ColorScan/45 is a 45/0 spectrophotometer. This instrument has been evaluated and adjusted by laboratory personnel to provide the most accurate measurements possible. It is capable of measuring a set of BCRA tiles to within roughly the NBS uncertainty in the tile calibrations. Any instrumental biases are then corrected using the technique of Berns and Petersen. Normally the only errors that need to be corrected are very small wavelength shifts and photometric nonlinearities.

The MatchScan II is currently undergoing a procedure similar to that which was carried out on the 45/0 instrument. The MatchScan has an integrating sphere geometry and reversible optics. The major problem in the evaluation of the MatchScan II is the lack of a complete set of calibrated standards from NBS for total reflectance measurements. The work is currently being undertaken using standard materials calibrated at two other laboratories.

The final instrument dedicated to the standardization program is the MCSL Goniospectrophotometer. This instrument has been redesigned with an upgraded light source, monochromator, and detector. It is the goal of the Munsell Laboratory to make this instrument into a reference spectrophotometer capable of making absolute spectral reflectance factor measurements. The wavelength scale will be set using line sources and lasers, and the photometric scale will be set based on the Fresnel reflectance from a quartz wedge. This instrument will increase the level of accuracy of the laboratory and allow direct transfer of calibration to the secondary standard spectrophotometers.

The standardization program has been formalized in the past year and a series of documents were prepared in early 1987 outlining our standardization capabilities. These documents were prepared to inform NBS and CORM of our plans for fulfilling the laboratories mission as a secondary standardization laboratory for colorimetric spectrophotometry. A format for certificates of calibration was also developed in the past year to provide a uniform presentation of calibration data and techniques.

The above mentioned work is part of the Munsell Laboratory's ongoing commitment to high quality measurement.

No standardization laboratory would be complete without proper facilities. The Munsell laboratory has dedicated one of its research laboratories to the standardization program. This facility will serve the purposes of the standardization program for the next year and a half. After that time the entire Munsell Laboratory will be relocated to the new Center for Imaging Science building which has just begun construction. A standards laboratory has been specifically designed into the new building. This laboratory will then house the spectrophotometric standardization program of the Munsell Color Science Laboratory.

Goniospectrophotometry

Sponsor: The Munsell Color Science Laboratory

In last year's annual report a project was discussed involving the goniospectrophotometric evaluation of white standard reference materials with respect to the CIE recommended view angle limits for the 0/45 measurement geometry. The results of this study indicated that even diffuse white materials differ significantly from Lambertian behavior in this small range of view angles. The results of this work were presented at the 1987 ISCC Williamsburg conference on appearance as well as the CIE 21st session in Venice (Grum, Fairchild, and Berns).

The results of the above mentioned work also led to concern over the calibration of goniospectrophotometers for absolute spectral reflectance measurements at angles other than 45/0 or 0/45. This led to the undertaking of a project designed to develop a primary transfer standard for reflectance goniospectrophotometry. This project was completed as a MS Thesis within the Munsell Laboratory (D. Daoust, RIT MS Thesis, July, 1987) and the results were presented orally by Mr. Fairchild at OPTICS '87, the OSA annual meeting. A paper is currently in preparation.

The results of the project are tables of absolute spectral reflectance factors for several combinations of illumination and view angles. These tables have been compiled for pressed barium sulfate and for a specific preparation of pressed PTFE powder. The complete data sets are available as Munsell Color Science Laboratory Technical Reports (Fairchild and Daoust, 1987).

Array Radiometry

Sponsor: New York State Center for Advanced Optical Technology

The Munsell Laboratory owns a Tracor Northern diode-array rapid scan spectrometer (DARSS) configured as a spectroradiometer. This instrument was the focus of an MS Thesis project completed in 1987 (W. Farrell, RIT MS Thesis, June 1987). This project involved the comparison of the Tracor Northern array radiometer with an Optronic Laboratories single channel spectroradiometer for the measurement of pulsed radiation sources. There was significant concern in the industrial community that array radiometers were not capable of accurate measurement of pulsed radiation sources.

To complete this project, the two radiometers were set up at opposite ends of the same optical bench, there bandwidths were matched as nearly as possible, and they were calibrated identically with the same standard lamp. A tungsten-halogen source was measured with each instrument several times. The source was chopped with an optical chopper and filtered different ways to look for spectral discrepancies. The two instruments provided virtually identical data for the tungsten lamp whether it was chopped or not. The next source measured was a xenon flash. Again, the results were virtually identical for both instruments. Finally, the phosphors of a CRT display were measured with each instrument and similar results. The only cases in which a discrepancy could be found were when the radiance of the test sources was simply too low for the limited sensitivity of the array radiometer. These results are presented in an MCSL Technical Report (Farrell and Fairchild, 1987).

The Munsell Laboratory also participated in a CORM intercomparison using the Tracor Northern instrument. This intercomparison involved the measurement of the spectral irradiance of a tungsten-halogen source and the determination of illuminance and correlated color temperature. The results of this intercomparison were reported at the 1987 CORM meeting.

The laboratory is very interested in making accurate determinations of the chromaticities of CRT phosphors. The Tracor Northern instrument is currently being fitted input optics to increase the input signal for the measurement of CRT displays. This project is currently being carried out as an undergraduate research project by Mr. Alec Greenfield.

Colorimetric Calibration of a CRT Imaging System for Color Appearance Research

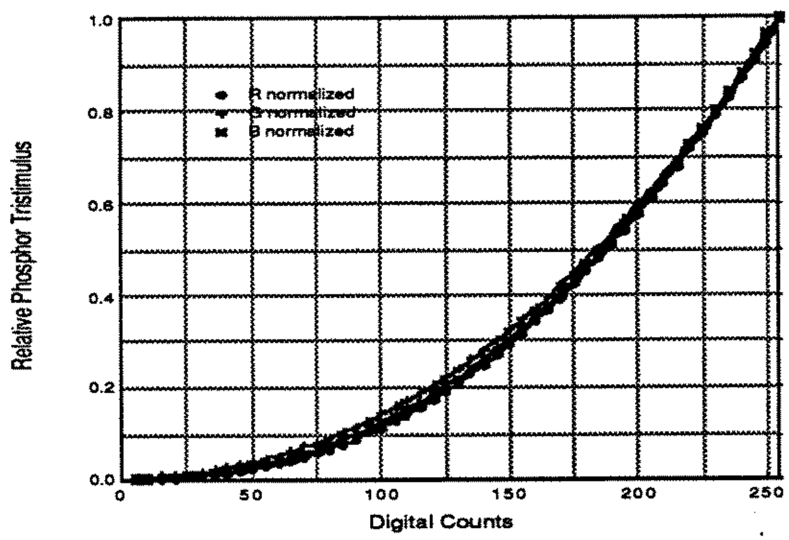
Sponsors: Munsell Color Science Laboratory, Xerox Corporation, Eastman Kodak Company

Self-luminous displays as stimulus generators offer tremendous potential in color science research. They can be used to address such fundamental and applied problems as the psychophysics of gloss, spatial and temporal factors affecting color discrimination, chromatic adaptation, perceptive color order systems, color constancy, and the human factors of color manipulation. In order to use these devices, one must know the transfer function between digital counts and absolute tristimulus values. These systems must be colorimetrically calibrated.

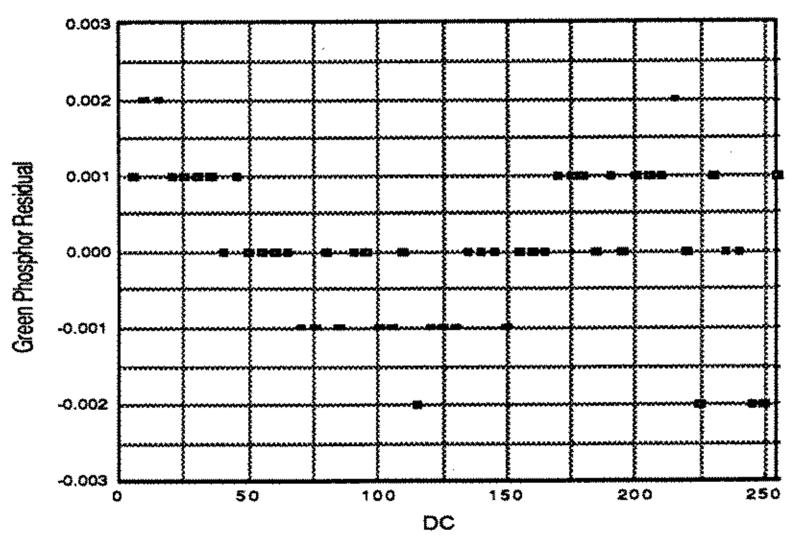
During the last two years, we have developed a full-color image processing system and determined its colorimetric transfer function. The system consists of an IBM PC-XT286 with 80287 numeric coprocessor, a Revolution Number Nine 512x32-bit image processing board, a Tektronix 690SR 19" monitor, and a Tektronix 650HRC 13" monitor. Stimuli are manipulated using a keyboard, joysticks, or a "mouse." Absolute spectroradiometric measurements are made using an Optronic Laboratories 740 system or a Photo Research PR710PC. Relative trichromatic measurements are made using a Minolta 2160 TV Color Analyzer.

Research in this area has been carried out by Mr. Ricardo Motta, a graduate student in Imaging Science. He has developed a comprehensive model which takes proper account of the electron-gun-amplifier's gain and offset. Calibration has been quite successful. Predicted and measured stimuli presented on the CRT are within measurement uncertainty. Examples of the relationship between digital counts and relative tristimulus values and the residuals of the calibration model are shown on the following page.

Tektronix 690SR Measured Phosphor Tristimulus vs Digital Counts



Green Phosphor Residuals for Gamma Model



This work will be presented at the ISCC/SID joint conference in Baltimore, MD and at the SPSE annual conference in Washington, DC, both in May, 1988. Several articles are currently in preparation. We are currently seeking further funding to use this tool in color appearance research.

Color Modeling of Electrophotographic Images

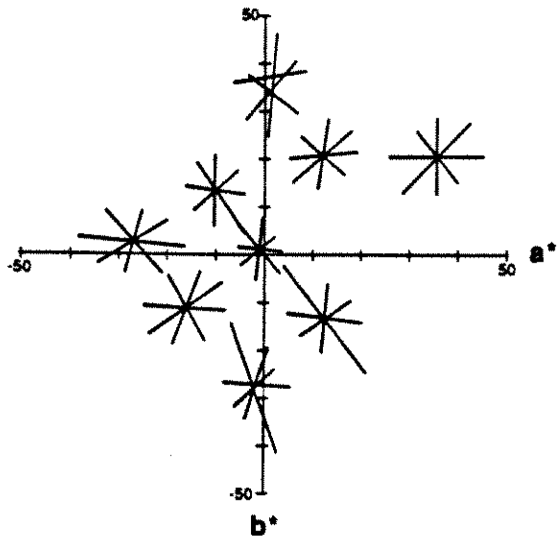
Sponsor: The Eastman Kodak Company

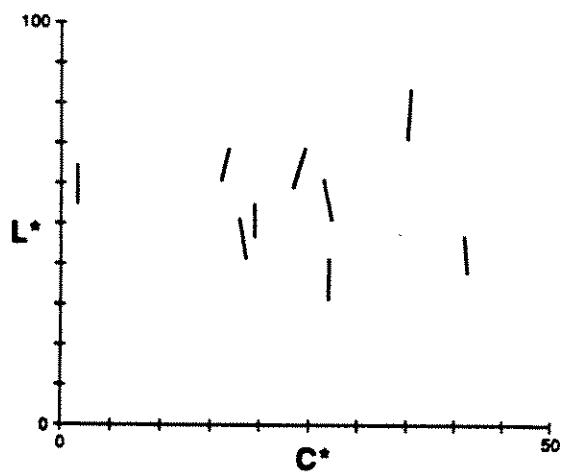
The accurate modeling of the color characteristics of toned electrophotographic images presents several problems. The image-forming layers are particulate, may scatter incident flux as well as absorb desired wavelengths, and are not uniform contiguous layers. Therefore, analytical techniques which may work well for other color systems, such as photography or coatings, may not apply well in electrophotography. The purpose of this research was to explore and compare three methods of color modeling: Kubelka-Munk turbid media theory for the limiting case of a transparent colored layer on an opaque support in which the calibration colorants are optimized using principal component analysis, Kubelka-Munk turbid media theory for the limiting case of an opaque absorbing scattering layer assuming the relationship between absorption and scattering and colorant amount are linear, and Neugebauer random dot theory. The first method is typically used at Kodak to model their photographic papers. The second method is typically used in the coatings and textile industries. The third method is typically used in the graphic arts. The most successful method in modeling a electrophotographic reproduction of the Macbeth Color Checker was the first method followed by the third method. This study was reported by Dr. Norman Burningham from Kodak and Dr. Berns from the Munsell Color Science Laboratory at the 1987 annual conference of the Society for Imaging Science and Technology.

Color Discrimination Psychophysics

Sponsor: E. I. du Pont de Nemours & Company, Finishes and Fabricated Products Department

Several years ago, we initiated research to scale industrial-magnitude color differences about nine color centers distributed in surface-color space according to a central composite design. Color difference pairs were constructed along five vectors for each center and compared to a near-neutral pair with a CIELAB total color difference of unity using the method of constant stimuli. Fifty color-normal observers made forced-choice pass or fail decisions comparing the magnitude of each pair to the anchor pair. The sigmoidal frequency of rejection functions generated for each vector direction were transformed to normal deviates using a probit model. Chi-square goodness-of-fit tests were performed and confidence intervals for the median pass-fail points were calculated. This research was completed in late 1986 and reported at the CIE Quadrennial meeting in Venice, Italy in 1987 (Berns, Alman, Snyder). An article for submission to Color Research and Application is in preparation. The resulting equal perceived color difference vectors are shown below 5 times their actual size.





We have initiated the second phase of this study which includes visual scaling of 45 color difference vectors about 10 additional color centers and further scaling about the original 9 color centers. The research is being conducted by Ms. Lisa Reniff, a graduate student in the color science, appearance, and technology program.

The results from both phases of the study will be used to model existing color difference equations and to develop our own equations. It is our intent to make the visual and colorimetric data easily accessible to the color science community.

Quantification of Industrial Illuminant Metamerism

Sponsor: The Munsell Color Science Laboratory

In 1985, we reported progress on quantifying illuminant metamerism by generating metameric mismatch galaxies for several industrial coloration systems (Berns, AIC Color 85 proceedings; Beering, RIT Senior Thesis). An article is nearing completion for submission to Color Research &

Application based on extended research. The purpose of this study has been to evaluate the metameric potential of commercially important illuminants by statistically analyzing sets of metamers and their metameric mismatch galaxies representative of 4 coloration systems. The illuminants studied were D65 representing daylight, illuminant A representing incandescent sources, F2 representing standard cool white fluorescent, and F11 representing three-narrow-band fluorescent. The 4 coloration systems studied were polyester textiles, nylon textiles, acrylic-enamel paint, and ABS polymer. The statistical analyses included multivariate analysis of variance and chi-square test for equality of covariance matrices. The size of the metameric mismatch galaxies was quantified by calculating the generalized sample variance (determinant) of each galaxy's covariance matrix.

It was found that each illuminant was statistically independent from one another. There was no statistical correlation between metameric galaxies. From this result, one can conclude that matches optimized to a single illuminant may not persist under secondary, tertiary, or quaternary illuminants. Furthermore, 3 chromatic colorant matches rank ordered to minimize mismatch under a secondary illuminant may not persist under a tertiary illuminant. In particular, one should not assume that a 3 chromatic colorant match in which daylight is the reference illuminant and where the mismatch under cool-white fluorescent is small will also have a small mismatch under incandescent or narrow-band fluorescent illumination.

Another finding concerned the lack of similarity between data bases. There was no statistically significant correlation between coloration systems under a given illuminant other than the reference illuminant. From this result, one can conclude that modeling illuminant effects such as color rendering and metamerism using a particular coloration system may not apply to other systems. For example, quantifying the color rendering properties of fluorescent lamps using a paint system such as the *Munsell Book of Color* may not apply to materials such as acid-dyed nylon or disperse-dyed polyester textiles.

The third area of analysis evaluated the tristimulus variance of secondary illuminants. One method to reduce illuminant metamerism is to add an additional colorant in the formulation and match tristimulus value X under the secondary illuminant as well as all three tristimulus values under the reference illuminant. The underlying hypothesis that tristimulus value X has the greatest variability for any secondary illuminant was tested using the 3 test illuminants A, F2, and F11. In most cases, the hypothesis was valid and from a practical perspective, this practice is statistically valid.

Finally, the choice of reference illuminant affects the size of resulting metameric galaxies. For the polyester system, the average galaxy was smallest when D65 was the reference galaxy as opposed to illuminants A, F2, or F11. From this result, one can conclude that 3 chromatic-colorant metameric matches which must persist under all 4 illuminants have the highest probability of being successfully formulated when D65 is the primary illuminant. Similar conclusions could be drawn in which D65,A, and F2 are the illuminants of interest.

In the future, we will be analyzing reflectance factor spectra from these coloration systems using principal component analysis. A data base of this type can have considerable utility in evaluating the color rendering properties of artificial lamplight and in optimizing the camera taking sensitivities of color measuring input devices which cannot be colorimetric.

Graphic Arts

The Munsell Color Science Laboratory is housed within the College of Graphic Arts and Photography. Consequently, we interact with the School of Printing Management and Science, the School of Photography, and our own Center for Imaging Science. During the last several years, we have become a resource for the School of Printing providing education and facilities for master's theses requiring colorimetric analysis. The following lists those printing students and their thesis topics who have utilized the Laboratory.

Mary Louise Bulger, "A colorimetric analysis of color variation due to changes in simulated ink trapping."

Jill Houghton, "An analysis of the effects of altering the dot gain characteristic curve of electrophotographic off-press proofs for critical color advertising material appearing in half-tone gravure publications."

Hans Kellogg, "The effects of solid ink density on shifts in hue in gray component replacement."

Patchanee Milikhao, "The application of CIELAB to the Study of Ink trapping."

Steve Viggiano, "Models for the prediction of color in graphic reproduction technology."

Shridhar Varde, "Colorimetric analysis of gray component replacement on newsprint."

Industrial Short Course & Seminars

In 1987, the Munsell Color Science Laboratory continued to offer its short course entitled; *COLORIMETRY: An Intensive Short Course for Scientists and Engineers.* This is a three-and-a-half day course designed to teach effective application of colorimetry to persons involved in coatings, textiles, polymers, reprographics, and electronic imaging. It is particularly useful for personnel currently using or contemplating using commercial color measuring instrumentation for quality control.

The course follows course notes prepared in the Munsell Laboratory as well as the textbook *Principles of Color Technology, 2nd Ed.* by Billmeyer and Saltzman. The objectives of the course are to: identify the important variables in visually evaluating color and color differences; derive in detail the CIE system of colorimetry; study the accurate calibration and correct use of current color measuring instruments; identify proper measuring technique for given materials; develop methods to apply colorimetry to quality control; and develop the principles of computer colorant formulation.

These courses continued to be very successful in the past year. They were offered in May and August and for a third time in November due to overwhelming demand. The Munsell Laboratory's short courses for industry have and will continue to be a major part of the laboratories dedication to a useful interaction with industry.

The faculty of the Munsell Color Science Laboratory also instruct many seminars throughout the year. Below is a list of some of these seminars from the past year.

1. *Introduction to Colorimetry*, presented at RIT Technical and Education Center seminar, "Color for Cost and Quality" September, 1987 by Fairchild, and November, 1987 by Berns.

2. *Colorimetry for Imaging Systems*, presented at RIT Technical and Education Center seminar, "Imaging Science" twice at Polaroid Corporation August, 1987, and at RIT November, 1987 by Fairchild.

3. *Introduction to Colorimetry*, presented at RIT Technical and Education Center conference, "Quality in Graphic Arts" May, 1987 by Fairchild.

4. *Color Reproduction Principles for Hard Copy Systems:* Colorimetry Section, presented by Imcotek, Inc., February, May, and July, 1987 by Berns.

5. *Principles of Imaging Science:* Colorimetry Section, organized by Eastman Kodak Company Training Department, March and September, 1987 by Berns.

6. *Colorimetry: An Intensive Short Course for Scientists and Engineers*, presented to 3M Industrial Minerals Product Division, August, 1987 by Berns.

Donations

The Munsell Color Science Laboratory has been generously supported by industrial and individual donors. Many of our research efforts, the maintenance of our facilities, and the support of students would not be possible without this support. The support from instrument manufacturers is particularly appreciated. Having state-of-the-art instrumentation makes our industrial seminars and our academic coursework very effective. Students from both programs gain extensive familiarity with them enhancing their current and future career potentials. From a research perspective, we recognize that colorimetry as a tool for estimating color perception is only effective when measurements are accurate and reliable. In our opinion, accurate color measurement is the foundation of all our research efforts.

The following lists our supporters during the time period of this annual report.

Unrestricted research grants and gifts

Xerox Corporation	$5,000
3M	$5,000
PPG Foundation	$5,000
Eastman Kodak	$5,000

Devices

Donor	Device	Value
Tektronix	650HRC color monitor	$5,300
Macbeth	2020+ spectrophotometer	$15,000 (estimated)
Photo Research	PR703A/PC spot spectroradiometer	$35,000(estimated)
Minolta	TV-2150 color analyzer (colorimeter)	$4,100
Pacific Scientific	TCM spectrophotometer, IBM PC-AT with enhanced graphics, color matching software	$35,000 (estimated)
Eastman Kodak Company	Tektronix 690SR color monitor	$5,000(estimated)

Other

Edwin Breneman..............1952-1986 J.O.S.A.
David Engdahl....................Color science library
Nick Hale............................IES lighting handbook,
ASTM volumes 14.02,06.01,
AATCC gray scales
Milton Roy..........................Instrument repairs
Pacific Scientific..........Instrument repairs
King Graphics...................Visual comparator

Oral Presentations

The following talks were presented orally during the period of this annual report:

1. "Goniospectrophotometric Characteristics of Common Transfer Standards with respect to CIE Normal/45 Geometry", Grum, Fairchild, and Berns, presented at ISCC Williamsburg Conference, Williamsburg, VA, 1987 by Berns.

2. "Metamerism in Art Conservation", presented at ISCC annual meeting, Philadelphia, PA, 1987 by Berns.

3. "Array Radiometery of Flash Sources", presented at ISCC annual meeting, Philadelphia, PA, 1987 by Berns.

4. "Visual Determination of Color-Discrimination Vectors using the Method of Constant Stimuli", presented at Center for Imaging Science Seminar Series, April, 1987 by Berns.

5. "Visual Determination of Color-Difference Vectors", Berns, Alman, and Snyder, presented at 21st session of the CIE, Venice, Italy, 1987 by Berns.

6. "Goniospectrophotometric Characteristics of White Reflectance Standards with respect to the CIE Normal/45 Geometry", Grum, Fairchild, and Berns, presented at 21st session of the CIE, Venice, Italy, 1987 by Berns.

7. "Development of a Goniospectrophotometric Transfer Standard", presented at the Optical Society of America 1987 Annual Meeting, Rochester, New York by Fairchild.

Technical Reports

We have initiated Munsell Color Science Laboratory Technical Reports to document our activities in our standardization program and to report research results inappropriate for publication. For example, data from our goniospectrophotometric measurements of white reference materials is over 60 pages in length.

1. *Long-Term Calibration of a Diode-Array Radiometer*, Fairchild and Berns, May, 1986.

2. *The Present Status and Future Directions of the Development of the Munsell Color Science Laboratory as an Intermediate Calibration Laboratory for Spectrophotometry*, Fairchild, January, 1987.

3. *Munsell Color Science Laboratory Comments on the NBS Response to the Fourth CORM Report on Pressing Problems and Projected Needs in Optical Radiation Measurements*, Fairchild, January, 1987.

4. *Munsell Color Science Laboratory Comments on NCSL Information Manual for the Design of a Standards Laboratory*, Fairchild, January, 1987.

5. *Investigation of the Accuracy of Array Radiometry for Measuring Pulsed Radiation Sources*, Farrell and Fairchild, July, 1987.

6. *Report on 21st CIE Session*, Berns, October, 1987.

7. *Goniospectrophotometric Data for Pressed PTFE Primary Transfer Standard*, Fairchild and Daoust, October, 1987.

8. *Goniospectrophotometric Data for Pressed Barium Sulfate Primary Transfer Standard*, Fairchild and Daoust, October, 1987.

Publications

The following is a list of the articles published by faculty and students of the Munsell Color Science Laboratory:

1. *Standards and Standardization in Optical Radiation Measurements*, Grum, Pearson, and Scharpf, 1985 TAGA Proceedings.

2. *Thermochromism of Ceramic Reference Tiles*, Fairchild and Grum, Applied Optics, 24, 3432(1985).

3. *Metameric Mismatch Limits of Industrial Colorants*, Berns, Mondial Couleur 85, proceedings of AIC, paper 40, 1985.

4. *Spectrogoniophotometric Properties of Standard Reference Materials*, Grum and Miller, "Mondial Couleur 85", proceedings of AIC, paper 53, 1985.

5. *A FORTRAN Program for Predicting the Effects of Chromatic Adaptation on Color Appearance based on Current CIE Recommendations*, Berns, Color Res. Appl., 11 (1986).

6. *Implementation of Recommended Ocular Exposure Thresholds for the Evaluation of Xenon Flashes*, Fairchild and Berns, J. Imaging Tech., 13 8(1987).

7. *Illuminating Artwork: Consider the Illuminating Source*, Berns and Grum, Color Res. Appl., 12, 63(1987)

8. *Goniospectrophotometric Characteristics of Common Transfer Standards with respect to CIE Normal/45 Geometry*, Grum, Fairchild, and Berns, proceedings ISCC Williamsburg, 43(1987).

9. *Visual Determination of Color-Difference Vectors*, Berns, Alman, and Snyder, proceedings 21st session of the CIE, Vol. I, 134(1987).

10. *Goniospectrophotometric Characteristics of White Reflectance Standards with respect to the CIE Normal/45 Geometry*, Grum, Fairchild, and Berns, proceedings 21st session of the CIE, Vol. I, 134(1987).

11. *Analysis of Color in Electrophotographic Images*, Burningham and Berns, proceedings SPSE 40th annual conference, 90(1987).

12. *Colorimetric Errors Due to the Microstructure of Additive Color Imaging Systems*, Motta, proceedings SPSE 40th annual conference, 94(1987).

13. *Development of Goniospectrophotometric Transfer Standard*, Fairchild, proceedings of OSA Annual Meeting, 132(1987).

14. *An Algorithm for the Optimization of Kubelka-Munk Absorption and Scattering Coefficients*, McCarthy, Walowit, and Berns, Color Res. Appl. 12, 340(1987).

15. *Spectrophotometric Color Matching Based on Two-Constant Kubelka-Munk Theory*, McCarthy, Walowit, and Berns, in press Color Res. Appl., (1987).

16. *Empirical Modeling of Systematic Spectrophotometric Errors*, Berns and Petersen, in press Color Res. Appl., (1987).