RICHARD S. HUNTER PROFESSORSHIP

MUNSELL COLOR SCIENCE LABORATORY

ANNUAL REPORT
1989

Rochester Institute of Technology

Center for Imaging Science
Chester F. Carlson Building
P.O. Box 9887
Rochester, New York 14623-0887

Table of Contents

Program Objectives

The Richard S. Hunter Professorship in Color Science, Appearance, and Technology was established in 1983 by a gift from Richard and Elizabeth Hunter. They recognized a need for perpetual education and research in this critical area. The Munsell Color Science Laboratory was established in 1983 after the dissolution of the Munsell Color Foundation, Inc. The aims and purposes of the Munsell Foundation as stated in its bylaws were "...to further the scientific and practical advancement of color knowledge and, in particular, knowledge relating to standardization, nomenclature and specification of color, and to promote the practical application of these results to color problems arising in science, art and industry."

Both endowed programs operate hand in hand on a daily level. The following four basic objectives help guide their activities: 1) To provide under-graduate and graduate education in color science, 2) To carry on research and development in color and appearance, 3) To establish a sound standardization program in areas where standards are either void or difficult to obtain from other sources, and 4) To provide an essential ingredient for the success of the first three -- namely, liaison with industry.

The Year In Review

During 1989, color science at Rochester Institute of Technology greatly expanded. The most dramatic change was our move during the Fall into the new Chester F. Carlson Center for Imaging Science, a 70 thousand square foot facility housing research laboratories, classrooms, an auditorium, and offices. The Hunter Professorship and the Munsell Color Science Laboratory operate under the umbrella of the Center for Imaging Science. Our new home has custom-designed space for our various activities in color measurement education, color reproduction, high accuracy optical radiation measurements, and visual psychophysics. Details of our facilities are listed in this report. This year, we expanded our staff by hiring a second associate scientist, Mr. Mark Gorzynski. His responsibilities will focus on computer hardware and software and multivariate statistics. We expanded our secretarial support to full time and hired Ms. Colleen McCabe. (Ms. Barbara Capierseo, who had worked for us part time, is the full-time secretary for the Center's Industrial Associates program.) Beginning in March, Mr. Po-Chieh Hung from the Konica Corporation has been studying and performing research with us for a two year period. As a visiting scholar, he will study psychophysical methods of scaling color image quality and help us colorimetrically calibrate many of our color imaging devices. Po-Chieh has extensive expertise in tetrahedral interpolation, a technique often used for calibration. Welcome Mark, Colleen, and Po-Chieh!

In May, the Munsell Color Science Laboratory Advisory Board convened for the first time in many years. Input from the Board has helped shape our current research efforts, our standardization program, and our Master's degree program. At the suggestion from the Board, the Color Science, Appearance, and Technology M.S. degree was shortened to Color Science. We have also restructured some of the courses to help students improve their communication skills through writing technical reports and oral presentations. Our standardization program will focus on providing primary transfer calibrations in visible spectrophotometry rather than absolute reference measurements.

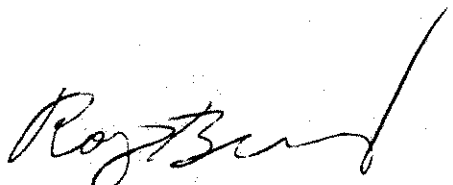
As color imaging devices become commonplace, we have recognized the need for industry to have opportunities to become educated about the principles of color reproduction. We introduced a new industrial course on the subject developed and taught by Dr. R.W.G. Hunt. The course was a great success and we plan to continue offering this important course in addition to our usual offerings.

This year, our research has focused on visual measurements. In order to have useful mathematical models, we desperately need more measurements of the visual system in which color judgments are performed in normal viewing situations. In this way, we can make progress in understanding the appearance of colored materials. During our first 5 years, we concentrated on obtaining proper tools to make accurate and appropriate physical measurements. During the next 5 years, we hope to concentrate on making visual measurements and to aid in our physical

measurements having better correlation. It is clear that fundamental visual measurements are most efficiently performed in academic environments. The future of our field depends on both industry and academia having access to data of these type.

Another important change during 1989 has been the increase in faculty, staff and students working with us. Including myself, we have 2 faculty, 3 staff, 1 visiting scholar, 6 full-time graduate students, 2 part-time graduate students, and 2 full-time undergraduate students, totaling 16! This is quite a change from 1983 where our total faculty and students was 3.

As always, the success of our programs would not be possible without strong industrial support. Many corporations and individuals have generously supported us both with computer and measurement equipment and cash donations. In particular, Mrs. Elizabeth Hunter continues to personally support the activities of the Hunter Professorship. Two new donors provided significant support: The Kollmorgen Foundation and Tektronix Corporation. Gifts received have been our main source of income for our graduate student stipends. These donations are an investment into the future of color science. External support goes hand in hand with our continued support from RIT administration, the Center for Imaging Science administration, faculty and staff, and of course, our students. Without the enthusiasm of our students, our motivation would surely falter.



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

RSB/cmm

February 5, 1990

Staff Activities

The following reports summarize the activities during 1989 of faculty, staff, and visiting scholars.

Mark D. Fairchild, Instructor, (716) 475-2784
B.S., Imaging Science, Rochester Institute of Technology, 1986.
M.S., Imaging Science, Rochester Institute of Technology, 1986.
M.A., Visual Science, University of Rochester, 1989.
Ph.D., Visual Science, University of Rochester, Any Day Now.

I spent several hundred hours of 1989 in darkened rooms at the University of Rochester setting up and running the experiments for my Ph.D. dissertation. It was all worthwhile as I am putting the finishing touches on my thesis and expect to complete my degree in the early part of 1990.

I also got a tremendous amount of exercise in 1989 by packing, moving, and unpacking my office and much of the Munsell lab in the heat of a Rochester August. By some stroke of genius, Roy had scheduled a vacation for the same time as our move, hmm? The dust is beginning to settle and we are pleased with our wonderful new facilities.

As you can see from the rest of this report, we've been very busy this past year. I think that's the way we like it. I'd like to thank all of our supporters for making the Munsell Color Science Laboratory not just possible, but a reality. I hope our activities are advancing the field of color science in some tangible way. With my Ph.D. studies winding down, you should be seeing more of me in the "color community" in the coming years.

Even though I spent much of 1989 in the dark, I must say the future appears bright.

Lisa Reniff, Associate Scientist, (716) 475-7188
B.S., Chemistry, Rochester Institute of Technology, 1986.
M.S., Color Science, Rochester Institute of Technology, 1989.

This year much of my Summer had been spent sorting, organizing, packing, moving, unpacking and reorganizing the Munsell Color Science Laboratory. The new facilities are a wonderful improvement, especially since many of the features were custom designed. (Do you know how may colors formica comes in?) A great advantage to the new facilities is the office space. I have been upgraded from a small desk in the front of the laboratory, sharing a computer with all the graduate students, to having an office (with door), window, swivel chair, computer, and telephone. It's heaven.

This past year also brought about my official completion of my M.S. in Color Science. I finally wore Roy down enough to sign my thesis on color differences. Thank-you Roy.

The majority of my time, when not moving, was spent learning about and setting up our calibration services for 45/0 reflectance factor measurements. After completing my first year of work, I am very excited and proud to continue working and learning in the Munsell Color Science Laboratory.

Mark E. Gorzynski, Associate Scientist, (716) 475-7186

A.S., Graphic Communications, Villa Maria, 1979.
A.S., Fine Arts, Villa Maria, 1980.
A.S., Photography, Villa Maria, 1981.
B.S., Imaging Science, Rochester Institute of Technology, 1988.
M.S., Imaging Science, Rochester Institute of Technology, 1990.

I only have a short time to report since I officially started with the lab in November. The move into the new building and the arrival of new computers and instrumentation has kept me on my toes most of the time. By the end of the year, our research computer network was up and activities were beginning. In between rebuilding operating systems, I did find time to organize my office and outline research for the coming year. This will include continuing work in the areas of CRT radiometry and colorimetry which were started while working as a graduate student.

Po-Chieh Hung, Visiting Scholar, (716) 475-7193

B.S., Electronic Engineering, Waseda University, 1981.
M.S., Control Engineering, Waseda University, 1983.
Working for Konica Corporation from 1983 to present.

Since I came to R.I.T. in March, I have been struggling to learn English. Guess my cultural shock! I could not understand what everybody was talking about. While I needed to take a minute to interpret a short English sentence, the conversation had flown to the moon. I could not catch up. But now I believe that I have succeeded in educating the color science people to speak English slowly to this poor English speaker, except for Mark Gorzynski. Thanks to him, I am getting familiar with fast English speaking.

Also, I have introduced "color engineering" on behalf of "color science" to the color science group. I have been developing practical color calibration algorithms for any electronic imaging device. Recently I finished developing the algorithm for input scanners and gave a talk at the Center for Imaging Science Industrial Associates meeting. Now it's the time to voyage into the awful scientific fields, where I am confused by contradiction between the practical and purely theoretical worlds.

Students

The following are students studying in color science.

FULL TIME GRADUATE

Mr. Seth Ansell, M.S. Candidate, Color Science

B.S., Imaging Science, Rochester Institute of Technology, 1989.

Ms. Amy North, M.S. Candidate, Color Science

B.S., Imaging Science, Rochester Institute of Technology, 1989.

Mr. Yan Lui, M.S. Candidate, Color Science

B.S., Physics, Shandong University, 1982; M.S., Color Science, Shandong Textile Engineering College, 1984.

Mr. Ken Parton, B.S./M.S. Candidate, Imaging Science

A.S., Engineering Science, Onondoga Community College, 1986.

Mr. Jason Peterson, B.S./M.S. Candidate, Imaging Science

A.S., General Science, A.A., Graphic Design, William Rainey Harper College, 1982.

Mr. Mike Stokes, M.S. Candidate, Color Science

B.S., Mathematics, University of Texas at Austin, 1989.

PART-TIME GRADUATE

Mr. Jim Adams, M.S. Candidate, Imaging Science

B.S., Physics, Monmouth College, 1979; B.S., Electronic Device Physics, Monmouth College, 1979; M.S., Optics, University of Rochester, 1984.

Mr. Jeffrey Wang, M.S. Candidate, Color Science

B.S., Graphic Arts, Chinese Culture University, 1982; M.S., Imaging Science, Rochester Institute of Technology, 1988.

FULL-TIME UNDERGRADUATE

Mr. Simon Choi, B.S. Candidate, Imaging Science

Mr. Robert Luciano, B.S. Candidate, Imaging Science

Funding

The Richard S. Hunter Professorship and 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

Elizabeth Hunter	$10,000
3M	$5,000
Eastman Kodak Company	$5,000
PPG Industries	$5,000
Tektronix Corporation	$10,000
Xerox Corporation	$20,000

Devices:

Donor	*Device*	*Value*
Barco Industries	"Calibrator" High-Resolution CRT	$8,420.00
LMT	Photonics Directory	$254.00
Color Curve Incorporated	Color Curve System	$690.00
Macbeth	Fluorescent Lamps	$192.00
Minolta	CR 221 & CS100 chroma meter	$12,000.00
BYK Gardener	Spare lamps, daylight filter	$150.00
Tektronix Corporation	ColorQuick Ink Jet Printer	$2,620.00

Research Contracts:

E.I. Du Pont de Nemours, Inc.

U.S. Department of Energy

Hewlett Packard

RIT Research Corporation

Research and Development

Research topics that were investigated in the past year are listed below in no particular order. The sources of funding are listed in brackets. The acronym MCSL means that the research was supported with the general research funds of the Munsell Color Science Laboratory. The acronym RSHP means that the research was supported through the Richard S. Hunter Professorship. We have provided a brief description on what each topic is about and this year's progress. Please refer to the publications list on pages 14 and 22 for references to more information on this research and feel free to contact any of us at the laboratory.

Chromatic Adaptation and Color Appearance
[Department of Energy, MCSL, Center for Imaging Science Industrial Associates, National Institutes of Health, Tektronix Corp.]
Mark Fairchild

An investigation of the spatial, temporal, and spectral properties of the mechanisms responsible for chromatic adaptation. Observer's were asked to generate achromatic appearing stimuli under a wide variety of adapting conditions. In the past year, all of the visual experiments were completed and the reports of the results and modeling are being prepared. This work should contribute to the modeling of color appearance in complex scenes and image displays.

Effect of Ambient Illumination and Image Color Balance on the Perceived Neutral-Point in Hybrid Imaging Systems.
[Franc Grum Memorial Scholarship, MCSL, RSHP]
Mark Gorzynski, Roy Berns, Mark Fairchild

This project involves the examination of the various viewing parameters that affect the perception of neutral in hardcopy and softcopy image displays. Observer's were asked to choose achromatic-appearing stimuli under various conditions using a softcopy image display, hard copy samples, and combinations of the two. The visual experiments were completed this past year and the results show some interesting differences in the color perception of softcopy displays, real objects, and renderings of real objects on softcopy displays. This project has also served as Mark Gorzynski's M.S. thesis.

Visual Determination of Color Difference Tolerances
[E.I. du Pont de Nemours Automotive Products Department]
Roy Berns, Lisa Reniff, Mitch Balonon-Rosen, Yan Liu

An ongoing project aimed at generating a data set of equal perceptual color differences of industrial size. Phase II of visual experiments has been completed and work is underway on combining the results of the first two phases and generating useful representations of the data. In addition, a project was undertaken to investigate the perception of color differences on a CRT display in comparison to the original experiments performed with automotive paint samples. Aspects of this work have served as Lisa Reniff's and Mitch Balonon-Rosen's M.S. theses.

Modeling of Systematic Spectrophotometric Errors
[Eastman Kodak Co., Xerox Corp., MCSL, RSHP]
Roy Berns, Lisa Reniff

Systematic errors in spectrophotometric measurements have been modeled and corrected using a linear regression technique. This technique can significantly improve measurement accuracy and inter-instrument agreement. Work continued on this project in the past year to improve our ability to implement this technique and to apply it to other instruments in a more general sense.

Colorimetric Calibration of a Flat-Bed Optical Scanner
[Konica Corp., MCSL]
Po-Chieh Hung, Mike Stokes

A 300 dots-per-inch color image scanner was colorimetrically calibrated for a limited set of input types. Since the sensitivities of the scanner are not a linear transform of CIE color matching functions, the scanner cannot be accurately calibrated without knowledge of the spectral reflectance properties of the input samples. The scanner was purchased and interfaced this year and a possible calibration technique using look-up tables and three-dimensional tetrahedral interpolation was studied.

Image Quality as a Function of Aspect Ratio for TV Displays
[MCSL]
Brant Nystrom, Mark Fairchild

This is an undergraduate research project aimed at studying the effect of image aspect ratio on the perceived quality of CRT images. Proposals for HDTV include changes in the aspect ratio based on the assumption that these changes improve image quality. However, surprisingly little research on this issue has been

performed. The psychophysical experiment, using paired comparison preference judgements, has been designed and set up and will be carried out early in 1990.

Spatial Uniformity Calibration of a Flat-Bed Optical Scanner
[MCSL, RSHP]
Simon Choi, Roy Berns

Stray light, flare, and detector responsivity variations cause scanned images to be spatially nonuniform. This work is another undergraduate research project designed to develop a technique for calibrating the spatial uniformity of a 300 DPI color image scanner. This project is necessary in order to be able to colorimetrically calibrate the scanner output for any pixel in an image and is currently in the preliminary stages.

Goniospectrophotometric Standardization
[Department of Energy, MCSL, RSHP]
Mark Fairchild, Jason Peterson, Roy Berns

Spectrophotometric measurements using non-standard illumination and viewing geometries require specialized materials or assumptions for accurate calibration and standardization. This is an ongoing project designed to develop a useful transfer standard for goniospectrophotometry. Work in the past year centered around developing a mathematical model of the large amount of data collected in these measurements. In addition, a paper on this topic is in preparation.

CRT Colorimetry
[LMT, Barco Ind., Minolta Corp., MCSL, RSHP]
Roy Berns, Mark Gorzynski, Seth Ansell

CRT displays are heavily used in our laboratory for psychophysical experiments. In order for these experiments to be successful, one must have accurate knowledge of the stimulus being displayed. This requirement has led to a tremendous effort in the Munsell laboratory aimed at measuring and modeling the colorimetric characteristics of CRT image displays. Work in the past year has centered around determining the uncertainty in our monitor calibrations, evaluating different techniques to determine the matrix elements relating monitor and CIE tristimulus values, and developing techniques for calibrating more than one spatial location on the monitor.

Effect of Luminance Level and Experimental Design on the Perceived Chroma of Munsell Samples
[RSHP]
Jason Peterson, Roy Berns, Mark Fairchild

This project's aim is to measure the changes in perceived chroma and possibly colorfulness as a function of adapting luminance level for simulated daylight illumination. This phenomenon is often referred to as the Hunt effect. The experiment will be carried out with several different techniques to assess their influence on the results. These include haploscopic matching, memory matching, successive inspection and simultaneous inspection. The results will also be used to evaluate the predictions of recent color appearance models. The visual experiments are underway for this project, which is also Jason Peterson's M.S. thesis.

Investigation of Observer Metamerism
[New York State Center for Advanced Technology in Optics, Kollmorgen Foundation, MCSL]
Amy North, Mark Fairchild

This project is designed to measure inter- and intra-observer variation in the measurement of color matching functions and will serve as Amy North's M.S. Thesis. Much time has been spent optimizing and calibrating the visual colorimeter. Measurements of color matching functions will begin soon and will utilize an abridged method reported previously. In addition, the measurements will be compared with similar ones to be made using the National Research Council (NRC) trichromator in Ottawa, Canada.

A Negative Feedback Control Model of Color Vision
[MCSL]
Yan Liu

Work has been underway for several years on a negative-feedback model of color vision. Much time in the last year has been spent writing up this work and it will serve as Yan Liu's M.S. thesis. In addition to deriving the physiological and psychophysical bases of negative-feedback control, new terminology will be introduced useful for predicting many color phenomena.

Development of a CIE Daylight Simulator
[MCSL]
Yan Liu

A more computationally efficient non-linear optimization algorithm has been developed for determining the combinations of filters in series and side by side required to produce a reasonable simulator for CIE illuminant D_{65}. This research is being translated into English and an article manuscript for submission to Color Research & Application is in preparation.

Modeling the Spectral Reflectance of Ink-Jet Printer Output
[Hewlett Packard Co.]
Ken Parton, Roy Berns

Ken Parton spent the summer of 1989 working for HP Corvallis Division where the initial plans for this M.S. thesis project were developed. The aim is to develop an analytical model capable of predicting the spectral reflectance of ink-jet printer output for various system parameters and input. This project is currently in the latter part of planning and should be completed in the coming year.

A Neural Network Model of Color Appearance
[MCSL]
Mark Fairchild

Artificial neural networks have been used to model many interesting phenomena. This project was designed to investigate the plausibility of using such models to predict color appearance. A successful model was developed for very simple viewing conditions. It remains to investigate whether this type of model can be used to account for adaptation and other more complex viewing parameters. In addition, the possibility of using this type of model for CIE-to Munsell conversion is being investigated.

What Determines Crossover Wavelengths of Metameric Pairs with Three Crossovers?
[Mobay Corporation, RSHP]
Roy Berns, Rolf Kuehni (Mobay Corporation)

Many studies have shown that the crossover locations of three-crossover metamers tend to occur in certain defined regions. This finding has led to hypotheses concerning fundamental aspects of the visual system. Calculations were carried out proving that crossover locations are dependent on the spectral properties of the metameric stimuli. For object colors, the spectral properties are determined by

colorant absorption bandwidths. Depending on the absorption bandwidth, crossovers can occur in nearly any region of the visible spectrum. Thus any relationship between crossover wavelengths and properties of the visual system such as maximal responsivities appears coincidental.

1989 Publications

The following is a list of reviewed articles and paper or abstract proceedings published by faculty, staff and students of the Munsell Color Science Laboratory (listed in bold) during 1989. Past publications are listed beginning on page 22.

M.D. Fairchild, "A Novel Method for the Determination of Color Matching Functions", *Color Res. Appl.* **14,** 122-130, 1989.

D.H. Alman, **R.S. Berns, G.D. Snyder,** and W.A. Larsen, "Performance Testing of Color-Difference Metrics Using a Color Tolerance Dataset", *Color Res. Appl.* **14,** 139-151, 1989.

R.S. Berns and R.G. Kuehni, "Dependence of Crossover Wavelengths of Metameric Pairs on Colorant Absorption Properties", Color 89, *proceedings of the 6th Congress of the International Color Association,* 178-180, 1989.

M.D. Fairchild, J. Peterson, and R.S. Berns, "A Principal Components Analysis of Diffuse Reflectance Standards", *Proceedings Council for Optical Radiation Measurements 1989 Annual Meeting,* 1989.

R.S. Berns, D.H. Alman, **L. Reniff, M. Rosen** and W.A. Larsen "Visual Determination of Color-Difference Vectors Using Probit Analysis: Phase II," *Inter-Society Color Council, Color Discrimination Psychophysics Williamsburg Conference, November,* 1989.

R.S. Berns, "A Comparison of Color Discrimination Experiments Using Surface Color Samples or Self-Luminous Displays," *Inter-Society Color Council, Color Discrimination Psychophysics Williamsburg Conference, November,* 1989.

1989 Presentations

R.S. Berns, "Dependence of Crossover Wavelengths of Metameric Pairs on Colorant Absorption Properties," 6th Congress of the International Color Association, Buenos Aires, Argentina, March, 1989.

R.S. Berns, "CRT calibration for hard-copy display," presented at Polaroid, June, 1989.

R.S. Berns, "Overview of Color Science Research Facilities and Objectives," Center for Imaging Science Industrial Associates meeting, October, 1989.

M.E. Gorzynski, "The Effects of Ambient Illumination and Image Color Balance on the Perceived White Point of Color Displays," Center for Imaging Science Industrial Associates meeting, October, 1989.

M.D. Fairchild, "Color Appearance in Image Displays," Center for Imaging Science Industrial Associates meeting, October, 1989.

P.C. Hung, "Colorimetric Calibration of a Flat-bed Color Scanner," Center for Imaging Science Industrial Associates meeting, October, 1989.

R.S. Berns, "Assumptions and Limitations in Using CIE Recommended Spaces for Color Reproduction," Center for Imaging Science Industrial Associates meeting, October, 1989.

R.S. Berns, "Mathematical description of color differences and color tolerances," presented at Dupont conference, "Expanding role of color technology at Dupont," October, 1989.

R.S. Berns, "Visual Determination of Color-Difference Vectors Using Probit Analysis: Phase II," Inter-Society Color Council, Color Discrimination Psychophysics Conference, November 1989.

R.S. Berns, "A Comparison of Color Discrimination Experiments Using Surface Color Samples or Self-Luminous Displays," Inter-Society Color Council, Color Discrimination Psychophysics Conference, November 1989.

R.S. Berns, "Assumptions and Limitations using CIE recommended Color Difference Spaces," presented at the Atlantic Chapter Society for Information Display's "Topics in the Application of High Quality Image Displays," November, 1989.

R.S. Berns, "Psychophysical Techniques to Quantify Color and Appearance," at Sherwin Williams technology symposium, December, 1989.

R.S. Berns, "A Principal Components Analysis of Diffuse Reflectance Standards", Council for Optical Radiation Measurements Annual Meeting, 1989.

Munsell Color Science Laboratory Advisory Board

The Munsell Color Science Laboratory Advisory Board is an advisory group composed of industrial and academic experts in color science and color aesthetics. Their role is to insure that the activities of the Munsell Color Science Laboratory are in concert with industrial needs, to evaluate the degree program in color science, to promote funding opportunities, and to provide employment opportunities to Color Science and Imaging Science graduates focused on color-related problems.

Dr. David H. Alman
E.I. du Pont de Nemours & Co.
P.O. Box 2802
Troy, NY 48007

Mr. Leroy DeMarsh
Eastman Kodak Company
Rochester, NY 14650

Dr. Henry Hemmendinger
438 Wendover Drive
Princeton, NJ 08540

Mr. Norbert Johnson
3M
3M Center 582-1-15
St. Paul, MN 55144-1000

Mr. Rolf G. Kuehni
Mobay Chemical Corporation
Mobay Road
Building 14, 1st Floor
Pittsburgh, PA 15205-9741

Mr. Calvin S. McCamy
Macbeth, A division of Kollmorgen Corp.
P.O. Box 230
Newburgh, NY 12550

Mr. Peter Engeldrum
Imcotek, Inc.
P.O. Box 66
Bloomfield, CT 06002-0066

Dr. Fred W. Billmeyer, Jr.
2121 Union Street
Schenectady, NY 12309

Mr. Richard S. Hunter
1703 Briar Ridge Road
McLean, VA 22101

Dr. Peter Kaiser
York University
Dept. of Psychology
4700 Keele Street
Downsview, Ontario MJ3 IP3
Canada

Mrs. Joy Turner Luke
Studio 231
Box 18 Route 1
Sperryville, VA 22740

Mr. Cornelius J. McCarthy
Milton Roy Company APD
820 Linden Avenue
Rochester, NY 14625

Dr. Klaus D. Mielenz
National Bureau of Standards
Bldg. 220 B-306
Gaithersburg, MD 20899

Dr. Yoshinobu Nayatani
Osaka Electro-Communication University
18-8 Hatsu-uho
Neyagawa, Osaka 572
Japan

Mr. Milton Pearson
RIT Research Corporation
75 Highpower Road
Rochester, NY 14623-3435

Mr. Ralph Stanziola
410 Clover Street
Neshanic Station, NJ 08853

Dr. Lee A. Cass
Xerox Corporation
800 Phillips Road
Bldg. 311-02J
Webster, NY 14580

Dr. Noboru Ohta
Fuji Photo Film Co., Ltd.
210 Nakanuma, Minami-ashigara
Kanagawa-ken 250-01
Japan

Dr. Alan R. Robertson
National Research Council
Division of Physics
Ottawa, Ontario KIA OR6
Canada

Color Science Courses

During this last calender year, several of the courses in the color science curricula were revised along with their names. The former two quarter sequence, Colorimetry I and II, was renamed to Applied Colorimetry and Theory of Color Measurement in order to reflect their course contents. The Color Modeling course was redesigned to cover this subject in a systems approach. Various mathematical models will be taught in conjunction with a color device. For example, the masking equations and Kubelka-Munk theory will be applied to a thermal dye diffusion printer; Grassmann's laws will be applied to modeling CRT's. Finally, Advanced Colorimetry has been replaced with Color Science Seminar in order to have students obtain experience in oral communications and critically reviewing current literature. The following lists the current catalog descriptions of the required courses for the M.S. degree in Color Science.

PIMC-700 4 Credit Hours VISION AND PSYCHOPHYSICS

Registration#0926-700

This course provides an overview of the human visual system and psychophysical techniques used to investigate it. Topics include: the optical design of the eye; mechanisms of photoreception; neural coding; processing of visual information; and experimental techniques. Emphasis is placed on the mechanisms of color vision.

PIMC-701 4 Credit Hours APPLIED COLORIMETRY

Registration#0926-701

An introduction to the measurement and specification of color. The CIE system of colorimetry is presented with an emphasis on its practical application to common problems in quality control, reproduction, imaging, and formulation. The laboratory stresses the instrumental measurement of color and appearance.

PIMC-702 4 Credit Hours THEORY OF COLOR MEASUREMENT

Registration#0926-702

This course is designed for students with an understanding of the applications of colorimetry and presents the fundamental research leading to modern color measurement techniques. Material is presented to provide the background for further studies and research and development in the field of color science. Topics include; daylight specification, instrumental geometries, color matching functions, color appearance, color difference, and metamerism.

PIMC-801 3 Credit Hours COLOR SCIENCE SEMINAR

Registration#0926-801

A seminar course in which the students will study the literature in particular areas of color science and present that material to the class. Topics will be chosen based on student interest and current issues in the field.

PIMC-802 **4 Credit Hours** **OPTICAL RADIATION MEASUREMENTS**

Registration#0926-802

An in-depth treatment of the instrumentation and standardization required for accurate and precise measurements of optical radiation. The optical properties of objects and radiation sources will be covered. The optical and electronic design of spectroradiometric and spectrophotometric instrumentation is discussed in detail. The use of standard reference materials for the calibration and evaluation of instrumentation is explored. The laboratory is heavily stressed with students fully analyzing the design and performance of various instruments.

PIMC-803 **4 Credit Hours** **COLOR MODELING**

Registration#0926-803

This course explores mathematical techniques for predicting the coloring of various imaging systems including self-luminous displays, reversal color films, thermal dye transfer printers, and color scanners. Emphasis is placed on both analytical-physical and empirical-phenomelogical approaches. Models include Kubelka-Munk turbid media theory for opaque, transparent, and translucent systems; Grassmann's laws for additive systems; and linear and higher order masking equations. Statistical techniques include multiple-linear regression and non-linear optimization via the simplex method. Accompanying laboratory stresses the characterization, calibration, and prediction of various imaging devices in a systems approach.

PIMC-890 **9 Credit Hours** **RESEARCH AND THESIS**

Registration#0926-890

Thesis based on experimental evidence obtained by the candidate in an appropriate topic as arranged between the candidate and the coordinator of the program.

A typical schedule of classes is the following:

	Fall	Winter	Spring
YEAR 1	PIMC 700 Vision and Psychophysics	PIMC 701 Applied Colorimetry	PIMC 803 Color Modeling
			PIMC 802 Optical Radiation Measurements
YEAR 2	PIMC 702 Theory of Color Measurement	PIMC 801 Color Science Seminar	
	PIMC 890 Research and Thesis	PIMC 890 Research and Thesis	PIMC 890 Research and Thesis

Short Courses

In 1989, the Munsell Color Science Laboratory introduced a new Industrial Course called *Principles of Color Reproduction: An Intensive Short Course* taught by Dr. R.W.G. Hunt. This 2-day course was directed at scientists, engineers, computer programmers, and managers. Participants mainly were from the photography, graphic arts and electronic imaging industries. The course was so successful this past year that we held a second course for the overflow students. Hereafter, we will offer the course yearly.

Again, our short course entitled *COLORIMETRY: An Intensive Short Course for Scientists and Engineers* was a success. This was a three-and-a-half day course designed to teach the effective application of colorimetry to persons involved in coatings, textiles, polymers, reprographics, and electronic imaging. The course stressed instrumental measurements particularly useful for personnel currently using or contemplating using commercial color measuring instrumentation for quality control.

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 at technical conferences and on site. Below is a list of these seminars from the past year.

1. *Colorimetry for Electronic Imaging Devices* presented at Eastman Kodak Company, Apparatus Division, February, 1989. (2 days)

2. *Color Reproduction Principles for Graphic Systems:* Colorimetry Section, presented by Imcotek, Inc., Boston, MA, May, 1989. (1 day)

3. *Colorimetry: An Intensive Short Course for Scientists and Engineers,* presented at 3M in St Paul, MN, June, 1989. (2 1/2 days)

4. *Colorimetry for Electronic Imaging Devices* presented at RIT, July, 1989. (1 day)

5. *Principles of Imaging Science:* Colorimetry and Color Reproduction Section, organized by RIT Training Department for presentation at General Electric, Government Systems Division, September, 1989. (1/2 day on site)

6. *Principles of Imaging Science:* Colorimetry Section, organized by Eastman Kodak Company Training Department, December, 1989. (1 day on site and 1 day at the Munsell Color Science Laboratory)

Site Visits to Rochester Institute of Technology

Representatives of the following companies visited to tour facilities and discuss color-related issues during 1989:

NHK (Japan Broadcasting Corporation), IBM, Adobe Systems Incorporated, Fuji Photo Film, Center for Advanced Television Studies(CATS), Tektronix, RR Donnelley & Sons Company, LMT, Textronix, Imcotek, Bowers Imaging, Rohm and Haas, Polaroid, Crossfield Lightspeed Incorporated, Philip Morris U.S.A., Macbeth, Konica Corporation, Dupont, Greytag, Toppan Printing Co., LTD., Barco Industries, Murikami, and Sharp Corporation.

Site Visits to Industry

Dr. Berns visited the following companies during 1989:

BYK Gardner, Eastman Kodak Company, Xerox Corporation, Polaroid, Dupont, and 3M.

Technical Reports

The following list Munsell Color Science Laboratory Technical Reports published to date. These reports contain various types of information and are written by faculty, staff, and students studying color science. The purpose of these reports is to provide additional information on subjects that are not appropriate for journal publications, either due to their information content or their 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.

9. *Evaluation of the LMT C1200 Tristimulus Colorimeter*, Gorzynski, August, 1989.

Past Publications

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

1985

F. Grum, M. Pearson, and N. Scharpf, "Standards and Standardization in Optical Radiation Measurements", *TAGA Proceedings*, 472-486, 1985.

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

R.S. Berns, "Metameric Mismatch Limits of Industrial Colorants", *Mondial Couleur 85, proceedings of the 5th Congress of the International Color Association*, paper 40, 1985.

F. Grum and Miller, "Spectrogoniophotometric Properties of Standard Reference Materials", *Mondial Couleur 85, proceedings of the 5th Congress of the International Color Association*, paper 53, 1985.

1986

R.S. Berns, "A FORTRAN Program for Predicting the Effects of Chromatic Adaptation on Color Appearance based on Current CIE Recommendations", *Color Res. Appl.* **11**, 82-88 (1986).

1987

M.F. Fairchild and R.S. Berns, "Implementation of Recommended Ocular Exposure Thresholds for the Evaluation of Xenon Flashes", *J. Imaging Tech.* **13** , 8-13 (1987).

R.S. Berns and F. Grum, "Illuminating Artwork: Consider the Illuminating Source", *Color Res. Appl.* **12**, 63-72 (1987).

F. Grum, M.F. Fairchild, and R.S. Berns, "Goniospectrophotometric Characteristics of Common Transfer Standards with respect to CIE Normal/45 Geometry", *proceedings ISCC Williamsburg*, 43-46 (1987).

R.S. Berns, D.A. Alman, and G.D. Snyder, "Visual Determination of Color-Difference Vectors", *proceedings 21st session of the CIE, Vol. I*, 62-65 (1987).

F. Grum, M.F. Fairchild, and R.S. Berns, "Goniospectrophotometric Characteristics of White Reflectance Standards with respect to the CIE Normal/45 Geometry", *proceedings 21st session of the CIE*, Vol. I, 134-137 (1987).

N. Burningham and R.S. Berns, "Analysis of Color in Electrophotographic Images", *proceedings SPSE 40th annual conference*, 90-93 (1987).

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

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

C.J. McCarthy, E. Walowit, and R.S. Berns, "An Algorithm for the Optimization of Kubelka-Munk Absorption and Scattering Coefficients", *Color Res. Appl.* **12**, 340-343 (1987).

1988

R.J. Motta and R.S. Berns, "The Colorimetric Calibration of a CRT Imaging System for Color Appearance Research", *proceedings ISCC - SID joint meeting* (1988).

R.S. Berns and R.J. Motta, "Colorimetric Calibration of Soft-Copy Devices to Aid in Hard-Copy Reproduction", *proceedings SPSE 41st annual conference* 266-269(1988).

A. Greenfield and R.S. Berns, "The Colorimetric Measurement of Color Cathode Ray Tubes Using a Tracor Northern TN-1710 Array Radiometer", *proceedings SPSE 41st annual conference* 270-271(1988).

M.D. Fairchild and Daoust, "Goniospectrophotometric Analysis of Pressed PTFE Powder for use as a Primary Transfer Standard", *Applied Optics* **27**, 3392 (1988).

M.D. Fairchild and Lennie, "Ganglion Cell Pathways for Rod Acuity", *proceedings of OSA Annual Meeting*, 132 (1988).

R.S. Berns and K.H. Petersen, "Empirical Modeling of Systematic Spectrophotometric Errors", *Color Res. Appl.* **13** , 243-256 (1988).

C.J. McCarthy, E. Walowit, and R.S. Berns, "Spectrophotometric Color Matching Based on Two-Constant Kubelka-Munk Theory", *Color Res. Appl.* **13**, 358-362(1988).

R.S. Berns, M.D. Fairchild, and M.M. Beering, "The Quantification of Illuminant Metamerism for Four Coloration Systems vis Metameric Mismatch Gamuts", *Color Res. Appl.* **13**, 346-357 (1988).

R.S. Berns, D.H. Alman, G.D. Snyder, and W.A. Larsen, "Evaluation of Color-Difference Equations Using a Visual Color Tolerance Dataset", *Book of Papers, Nat'l. Tech. Conf., Tex. Chem. Col.*, 115-117, 1988.

Facilities

The Munsell Color Science Laboratory is housed on the third floor of the Chester F. Carlson Center for Imaging Science, at the Rochester Institute of Technology. This is a new facility, dedicated on October of 1989 in the memory of Chester Carlson, inventor of Xerography, and will serve as a comprehensive center for education and research in imaging science. Color science is a major research interest of The Center for Imaging Science, and the Munsell Color Science Laboratory established at RIT in 1983 is located within it. The main laboratory contains many color measuring instruments, while small rooms off the main area are dedicated to specific tasks. These areas contain low and high resolution image processing and display systems with input and output devices, spectroradiometric and photometric measurement equipment and visual apparatus. One room was specially designed for high accuracy optical radiation measurements and houses several spectrophotometers used for research and calibration services, and goniospectrophotometric research. Two other laboratories within the center for imaging science are involved in color science research. They are the Electronic Imaging Laboratory founded by Xerox Corporation and the Electronic Printing Laboratory founded by Konica Corporation. Color Science research and education through the color science master's degree program and industrial seminars is conducted in the Munsell Color Science Laboratory and associated laboratories. As of December 31, 1989, the list of equipment is given below.

Optical Properties of Materials

Applied Color Systems Spectro-Sensor II Spectrophotometer
400-700 nm, d/0, single beam, interference wedge
Chroma-Calc color matching software for paints, textiles, and inks
Partial Donation by Applied Color Systems

Cary 17D Spectrophotometer
186-2650 nm range, digital and analog
Donation by Eastman Kodak Co.

Cosar Pressmate I Densitometer
Hand held, Status T, reflectance
Donation by Cosar Corp.

Cosar 75 CompuPlus Densitometer
Status A and Status M, reflectance head attachment
Donation by Cosar Corp.

Diano Match Scan II Spectrophotometer
380-1000nm, d/0, reversible optics, double beam, grating monochromator
Donation by MiltonRoy APD

General Electric Recording Spectrophotometer
380-700nm, 0/d, analog, double-beam, D &H tristimulus integrater

HunterLab Dori-gon Meter D47-6
Abridged Goniophotometer
Donation by Hunter Associates Laboratory

HunterLab D25A-9 Tristimulus Colorimeter
45/0, 4 filtered detectors, Ill C
Donation by Hunter Associates Laboratory

HunterLab D25D-2 Tristimulus Colorimeter
45/0, 4 filtered detectors, Ill C
Donation by Hunter Associates Laboratory

HunterLab Labscan Spectrophotometer
400-700nm range, 0/45, interference wedge monochromator
Donation by Hunter Associates Laboratory

HunterLab Modular Model D48-7 Gloss Meter
20 and 60 degree heads
Donation by Hunter Associates Laboratory

IBM Model 9420 Spectrophotometer
190-900nm, analytical, integrating sphere attachment
Donation by IBM

Macbeth 1500 Spectrophotometer
400-700nm, d/0, 16 diode array detector
Donation by Macbeth

Macbeth 1500/Plus Spectrophotometer
400-700nm, d/0, 16 diode array detector, CIE to Munsell software
Donation by Macbeth

MCSL Goniospectrophotometer
total control of illumination and viewing angles
Partally donated by Eastman Kodak Co. and funded by New York State Center for Advanced Technology

MiltonRoy ColorScan Spectrophotometer
350-780nm, d/0, double beam, grating monochromator
Donation by MiltonRoy ADP

MiltonRoy ColorScan/45 Spectrophotometer
350-780nm, 45/0, double beam, grating monochromator
Donation by Milton Roy APD

Minolta Chroma Meter CR-221 Colorimeter
compact, 45/0, D65, C
Donation by Minolta Corp.

Optronic 746-D Spectrophotometer
280-2500nm, 0/d, 3 grating monochromator
Funded by New York State Center for Advanced Technology

Pacific Scientific Colorgard System 1000 Colorimeter
0/45
Donation by Pacific Scientific

Pacific Scientific Glossgard II
20, 60, 85 degree units
Donation by Pacific Scientific

Pacific Scientific Spectrogard Spectrophotometer
d/0, 380-720nm, grating monochromator, color matching software
Donation by Pacific Scientific

Pacific Scientific The Color Machine Spectrophotometer
380-720nm, 45/0 grating monochromator, 32 diode array detector, color matching software
Donation by Pacific Scientific

Photodyne 99XL Densitometer
Portable, fiber optic, transmission or reflection

Radiometry

LMT C1200 Colorimeter
17 filtered detectors, 2° obs.
Donation by LMT

Minolta Chroma Meter II Incident Colorimeter
hand held, 2^{o} obs.
Donation by Minolta Corp.

Minolta Chroma Meter CS-100 Colorimeter
hand held, spot reflex viewing.
Donation by Minolta Corp.

Minolta TV Color Analyzer TV-2160 Colorimeter
4 filter, designed to measure CRT, individual phosphor measurement, 2^{o} obs.
Donation by Minolta Corp.

Optronic Model 740 Spectroradiometer
280-1100 nm range, double monochromator, calibrated detector
Donation by Optronic Laboratories Inc.

Photo Research PR-703A Spot Spectra Scan Spectroradiometer
256 diode-array, spot reflex viewing
Donation by Photo Research

Photo Research PR-1500 SpotMeter Radiometer/Photometer
PMT, Pritchard optical System
Donation by Photo Research

Schoeffel Monochromator (2)
blazed at 500nm and 300nm

Tracor Northern DARSS Spectroradiometer
240-870 nm range, 512 diode-array
Funded by New York State Center for Advanced Technology

<u>Visual Apparatus (partial list)</u>
Breneman Visual Colorimeter
chromatic adaptation apparatus
Donation by Eastman Kodak Co.

Japan Color Research Institute Chroma Cosmos 5000 (2)
Munsell based color order system

Dianolite Viewing Booth
3 booths, daylight tungsten and UV lamps
Donation by MiltonRoy APD

D & H Color Rule (3)
metameric slide rule, evaluation of observer and illumination variability

Farnsworth-Munsell 100 Hue Test (2)
color discrimination test

ISCC Color Aptitude Test
color discrimination and aptitude test

Isochromatic Plate Color Blindness Charts (many)
Ishihara, Dvorine, American Optical Co.

Lovibond Tintometer Visual Colorimeter (2)
Model E and Mark 3, Subtractive
Donation by Tintometer Co.

Macbeth SpectraLight Viewing Booth
D65, CWF, horizon, narrow band fluorescent

Macbeth SpectraLight Viewing Booth
D75, CWF, Horizon, UV
Donation by Macbeth

MCSL Laser Visual Colorimeter
laser primaries, measurement of color matching functions
Funded by New York State Center for Advanced Technology

Munsell Book of Color
glossy and matte editions,
Donation by Munsell Color Company

Nagel Anomaloscope
testing of protan and deuteran color vision defects

OSA Uniform Color Scales
color order system

Color Display and Reproduction

Barco "Calibrator" Color Monitor
19V, black dot mask, DAF inline gun, 48-66 Khz H, 40-120 Hz V
Donation by Barco Industries

Howtek Scanmaster Color Scanner (Sharp JX450)
300DPI flat bed color scanner

Kodak SV-6500 Still Video Printer
color thermal transfer Printer

Matrix ProColor Film Recoder
35mm, digital

Number 9 Revolution Graphics Display Controller
1 Mbyte frame buffer, 10 MHz bandwidth, 8 bit R,G,B DAC.
Partially funded by Xerox
IBM PC AT host computer

Pixar II Image Computer
12 Mbyte frame buffer, 480 Mbyte/sec. bandwidth, 10 bit R,G,B DAC.
Sun Microsystems 3/160 host computer

Sony GDM-1950 Monitor
16V, Trinitron CRT, 48/63 Khz H, 60 Hz V

Sun Microsystems TACC-1 Application Accelerator
8 Mbyte frame buffer, 10-100 MHz bandwidth, 8 bit R,G,B DAC.
Donation by Sun Microsystems
Sun Microsystems 3/260 host computer

Tektronix 650HR-C Color Monitor
13V, Trinitron CRT, 6 MHz bandwidth.
Donation by Tektronix

Tektronix 690SR Color Monitor
19V, dot mask, delta gun, 15-17 KHz H, 45-65 Hz V
Donation by Eastman Kodak Co.

Tektronix Color Quick Ink-jet Printer
216 DPI, CMYK ink system
Donation by Tektronix

For More Information

For more information concerning the activities of the Richard S. Hunter Professor or the Munsell Color Science Laboratory, please contact:

Dr. Roy S. Berns
Richard S. Hunter Professor
Director, Munsell Color Science Laboratory

Rochester Institute of Technology
Munsell Color Science Laboratory
Chester F. Carlson Building
P.O. Box 9887
Rochester, New York 14623
Telephone: 716-475-2230
FAX: 716-475-5988

Ms. Colleen McCabe
Secretary, Munsell Color Science Laboratory

Rochester Institute of Technology
Munsell Color Science Laboratory
Chester F. Carlson Building
P.O. Box 9887
Rochester, New York 14623
Telephone: 716-475-7189
FAX: 716-475-5988