MUNSELL COLOR SCIENCE LABORATORY

RICHARD S. HUNTER PROFESSORSHIP

ANNUAL REPORT
1992

Rochester Institute of Technology

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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 basis. The following four basic objectives help guide their activities: 1) To provide undergraduate and graduate education in color science, 2) To carry on research and development in color and appearance, 3) To maintain the facility to perform spectrophtometric, colorimetric, and geometric measurements at the state of the art and 4) To provide an essential ingredient for the success of the first three — namely, liaison with industry.

The Year In Review

1992 was a year of self-evaluation. This was somewhat predicated by knowledge I gained through attending a quality seminar presented by W. E. Deming. Along with 999 other students, I learned about quality circles, continuous improvement, and management philosophy and responsibility. It was very exciting to experience Dr. Deming firsthand. I soon had several opportunities to apply my new knowledge. The first occurred while grading laboratories. A new student turned in his first write up and I found that the style and content were not what was required. In the past, I would give a low grade with a written explaination. Deming would argue that this would be demoralizing to the student, squelch his motivation, and subvert his productivity. Instead, I wrote "redo" on his work and spent time with him to explain what I wanted. To my great surprise, the redone write up was excellent as were all of the other required write ups. More importantly, he became very enthusiastic about the subject and a part of our research program. I'm sure this wouldn't have occurred if I had taken my past approach to grading. I also learned to appreciate how each member of the Laboratory contributes to our total environment of education and research. The success of an individual should be based, in large part, on the success of the team. Thus although I have the honor of "directing" the Laboratory, our successes come from all of us learning to interact effectively.

Another issue during the seminar was the importance of communication that is exemplified by the quality circle. Accordingly we began a newsletter, The *Chroma Zone*, so that we could have more frequent contact with our supporters. In it are contained recent research results, editorials, and related activities.

During the year, we evaluated our M.S. program in Color Science to determine whether we were meeting the needs of our constituency and to improve our teaching efficiency. After polling the Munsell Color Science Laboratory Advisory Board, our students and staff, Mark and I made several changes to the curriculum. The first was to introduce a non-thesis option. For some students (especially part time), they already have extensive research experience. For these students, the thesis can be replaced with additional elective coursework and an independent study. We have also dropped the Theory of Color Measurement course and added a course on Color Appearance to reflect the emergence of color appearance models as an important area of knowledge. The details of all the changes can be found within the report.

Another internal event was the formation of the RIT Color Consortium. Its scope is to increase interaction among faculty and staff engaged in color activities on campus. Participants have come from the School of Photography, the School of Printing Management and Science, the National Technical Institute for the Deaf, the School for American Crafts, and the School of Fine and Applied Arts. We are trying to identify ways to share resources and learn about each others' definition of color. In a sense, the Color Consortium is a micro-ISCC.

The third Franc Grum Memorial Scholarship was presented to Ms. Audrey Lester. Audrey has a background in chemistry and quite a bit of industrial experience. She has returned to academia after putting her career on hold to start a family. Since joining the Laboratory, she has shown tremendous leadership and research potential, two traits synonymous with Franc Grum. A second endowed scholarship was established toward the end of the year. The Kollmorgen Foundation divested its assets to RIT to establish the Macbeth-Engel Fellowship in Color Science. This will be a competitive scholarship to support graduate research in color. We are very thankful to Kollmorgen and hope to continue the tradition of supporting high-quality scholarship begun by Kollmorgen several decades ago.

Our research in colorimetric-based color reproduction and color-appearance psychophysics continues to generate support and interest. Mark has established a research program to evaluate appearance matching between soft copy and hard copy supported by Eastman Kodak, and between soft copy and projected slides supported by the National Science Foundation, New York State, and Industry. In order to support his efforts we have been active in device characterization. This year we purchased, via these research projects or received as gifts, a Kodak dye-diffusion thermal-transfer printer, MGI Solitaire film recorder, and Howtek desktop drum scanner. All require colorimetric characterization and I am finding that models successful for describing the coloration of materials also apply to imaging devices. We also received a two year grant from Dupont Imaging to evaluate the tradeoffs between densitometric, colorimetric, and multispectral scanners for high-quality color reproduction. An area I am interested in applying our knowledge of colorimetric color reproduction towards is the problem of reproducing paintings accurately in posters, textbooks, and catalogs. I have visited with the Getty Conservation Institute and the Art Institute of Chicago and, hopefully, 1993 will find the Laboratory engaged in this area of research and development.

As always, the scope and quality of our activities would not be possible without the financial and intellectual help from all our friends and supporters. Within the Annual Report is a listing of our supporters during 1992. In particular, I would like to thank Mrs. Elizabeth Hunter, Kollmorgen, Dupont, and Kodak for their significant support of color science research and education. I also would like to thank our students and staff for their dedication and hard work. Without them, most of our achievements would not have been possible.

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

January 1993

Faculty and Staff Activities

The following reports summarize the activities during 1992 of faculty, staff, and visiting scholars.

<u>Mark D. Fairchild, Assistant Professor, (716) 475-2784</u>

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, 1990.

Another year, another annual report. Time seems to be moving faster than it used to. I think that has something to do with Weber's Law, but I'll leave that for another paper. Last year, I was foolish enough to suggest that perhaps my life was settling down. There are many aspects to a university ... none of which have anything to do with settling down. Life at a university means getting used to changes and controversy.

Changes at a university are many fold. One of the best, and at the same time worst, is the constant change in researchers in our laboratory. Students, visiting scholars, staff, and administrators are constantly coming and going as time and circumstance bring them to MCSL and take them away again. More than anything else in the past year, I have learned how to keep a coherent research program flowing through these constant changes. Believe me, that is no small feat.

Controversies are also not sparse in a university setting. There are the never ending internal battles over topics such as curriculum, the definition of imaging science, the fundamental nature of color science, and square footage. I won't bore you with the details of such pedantic controversies. I have also been involved in my share (or perhaps more than my share) of controversies involving the color science community as a whole. The first of these was an exchange of letters to the editor of *Color Research and Application* with Professor Nayatani. It seems that he has some disagreements with some of the statistical analyses that Elizabeth Pirrotta and I included in our paper on the lightness of chromatic object colors. While it appears the exchange of letters did little to change either of or minds on the topic, I am sure that both of us have now seen things from another point of view and perhaps the readers of *CR&A* will gain some insight into how statistics can be used to achieve differing objectives. William Thornton published a three-part article in *CR&A* and made several presentations at the 1992 ISCC annual meeting on his work on color matching functions. While he presented some useful data, many of his conclusions exceeded the bounds of his experiments. This has led to much confusion in the color community regarding the applicability of basic colorimetry. Since I have collected and published some relevant data, I was encouraged to write a *Color Forum* for *CR&A* attempting to clarify some of these issues. Of course, being a glutton for punishment, I jumped right into the fray. I prepared a *Color Forum* on the topic which has been accepted for publication and will appear in 1993. Although the

Color Forum was not a letter to the editor on Thornton's papers, the editor has seen fit to let him respond in writing in the same issue. I am anxious to see that response and to see how this particular controversy unfolds in the color science community. Lastly a small controversy came up with the ISCC. Several participants noted the paucity of brewed alcoholic beverages at the 1992 Princeton meeting and I was forced to write a column in our newsletter, *The Chroma Zone*, suggesting that perhaps we have an ISCC wine, <u>beer</u>, and cheese reception at future meetings in honor of Lovibond (who was a brewer and invented a colorimeter). I am happy to report that we will have the option of consuming "Lovibond Golden Amber" at the 1993 ISCC meeting. These important scientific issues must be addressed properly.

In summary, in 1992 I taught some courses, did some research, served on lots of committees, wrote some papers, gave some talks, and tried to keep things interesting in the color science world. I've really enjoyed almost all of it (I could do without most of the committees). Welcome to all of the new faces around MCSL and I wish all of those that have left or are leaving us the best of luck in their future endeavors. I hope everyone's experiences in our laboratory are positive ones. Lastly, thank you to all who have supported me and MCSL over the past year.

<u>Lisa Reniff, Associate Scientist, (716) 475-7188</u>

B.S., Chemistry, Rochester Institute of Technology, 1986.

M.S., Color Science, Rochester Institute of Technology, 1989.

As the snow continues to fall in upstate New York, it is a good time to reflect on the past year. However, my memories of this year start to intertwine and blur with the past years. Buying equipment, helping students, answering phone calls, installing software, and keeping track of events, people and things are all common denominators and important in their own right. One of the events that stands out significantly is the continuing work performed in the area of accurate measurement of materials. This past year I have been training Colleen to perform the many routine measurements. She has become very good at making repeatable measurements. Although this is not terribly exciting work, I have managed to fool Colleen into believing that it is.

I have been excited over the investigation into the temporal response of chromatic adaptation that Mark and I have performed this year. Our first attempt was a flop due to large observer uncertainty. The experiment was redesigned so the observer’s responses were constrained to movement with one degree of freedom (as was determined allowable in the previous experiment) instead of two. We anticipate presenting the results of this work at OSA next fall.

I was fortunate enough to attend the Williamsburg conference last spring (it was still winter up here) and delve into the midriff of problems involved in the pursuit of reproducing color images. I found the format of the conference very conducive to good discussions, including an interesting by-product on the effect (negative and positive) of proprietary research.

This coming year will a bring new dimension to my responsibilities. I will be teaching a course on optical radiation measurements. This was due to a rearrangement of the masters curriculum in order to make a more logical study plan for the students. I am looking forward to this new teaching challenge; as the adage goes 'you don't know the material until you can teach it'. I continue to enjoy my job, and that is due in part to having Roy as my "boss".

...time for another year!

Mike Stokes, Associate Scientist, (716) 475-7186

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

M.S., Color Science, Rochester Institute of Technology, 1991.

The last year has gone by quickly for me with my time at the Munsell Lab split between providing students with both color and computer support, writing software utilities, installing new equipment and software, and performing basic color research. In addition to these tasks, I squeezed in time to design and create a new color display outside of Roy's office demonstrating various areas of our current research including color appearance modeling, compression, color spaces, and color manipulations in CIELAB.

Providing student support included both the daily run-of-the-mill problems and questions and some basic software coding to help implement their thesis research. The software support included comparing color appearance models using UNIX shell scripts, integrating JPEG compression algorithms into our existing color reproduction software base, and coding a multi-ink spectral neugebauer model. I've found all of this work fascinating in both variety and difficulty.

On a more general level, a significant portion of my time was spent creating a number of software utilities for both the Macintosh and UNIX environments. The Macintosh utilities include helping Mark code a set of basic Photoshop® plug-in filters for color space transformations and an interface to Gretag SPM model spectrophotometers. The UNIX utilities were extensions of the color reproduction software that I had written previously. These extensions include the ability to manipulate spectral images, user definable storage and computational precision for color space transformations and manipulations, and input/output utilities for Pixar, ppm, and plain text files.

Much of my research this last year has been on the Solitaire film recorder. This includes studying a method to set up the internal controls for intensity and tone control and deriving an analytical model to convert colorimetric values to digital counts. Finally I published an industrial note in *Color Research and Application* on an efficient method for computing ΔH^*_{ab}.

Toru Hoshino, Visiting Scholar

B.S., Imaging Science and Engineering, Chiba University, 1986.

Working for Konica Corporation from 1986 to present

Spending the last twenty three months, I characterized a dye diffusion thermal transfer printer, calibrated a scanner, and finished one color gamut mapping experiment. I spent most of the time writing software and debugging, I think. For people who are going to do this kind of research, I'd like to express how painful it was. After finishing all processes of measurements, computations, and other things very carefully, reproduced images didn't sometimes look OK. Why? I don't know. Let's start debugging again. Do I want to get rid of doing these things, escape to Aruba, and live there enjoying windsurfing every day? Definitely. But, I have to go back to Japan and work for Konica with my new career of color science.

With good facilities and people, I learned not only fundamental color science but also application techniques for color reproduction and image processing. I could apply most of the things I learned here to my color reproduction software.

I'd like to keep expanding my knowledge of color science, and try to contribute to Konica which gave me this opportunity of being here.

Taek Gyu Kim, Visiting Scholar, (215) 388-5334

B.S. Imaging and Photographic Technology, Rochester Institute of Technology, 1987.

M.S. Candidate, Imaging Science, Rochester Institute of Technology.

Working for DuPont from 1989 to present.

It was a great experience for me being a visiting scholar at MCSL. I think I absorbed an enormous amount of knowledge in the color area for one year. Meaningful discussions with colleagues also helped to expand my knowledge in the field.

Studying and performing experiments on color appearance models was an adventure. Without so many agonizing nights and weekends to understand models, code them, debug and run, I could not have done the experiment. I had to watch out for so many things to execute the experiment correctly. When the first images came out with alot of out-of-gamut colors, when the diffuser arm was broken in the middle of the experiment, and when solenoids burned out, it was really embarrassing.

After all, I really appreciate the help that I got from MCSL people. I am planning to publish the work that I have done at MCSL. I hope to meet all DuPont's needs with the knowledge that I got from MCSL, meanwhile continuing such a relationship with Roy and Mark, et al.

Hiroshi Uno, Visiting Scholar

B.S. Electrical Engineering, Science University of Tokyo

M.S. Electrical Engineering, Science University of Tokyo

Working for NEC Corporation from 1984 to present.

Being with energetic, competent, and kind people here at the Center for Imaging Science, I have spent the last five months rather meaningfully since I came from Tokyo. Living and studying in this beautiful country, I have learned a lot and enjoyed much culture shock(!?). However, I am gradually growing accustomed to American culture and "Winter of Rochester," I might add. Recently, my English seems to change from mumbling to kinds of speaking. However, I still feel awkward to call people by their first name, because Japanese don't call each other by their first names socially. Imagine, if I would call my boss by his first name, I could not be in my office, forever.

My resolution of this year is to become a Man of Color Science. I have been dealing with monochrome technology in NEC, so I will master color science here and develop easier color matching design method for O.A. equipment. In addition, I am interested in color halftone technology, I will develop a new one that expresses color images more beautifully and can be compressed effectively.

Through these activities, I do hope I can contribute to RIT academic activities and enjoy the remainder of my seven months here.

Students

The following are students studying color science.

FULL TIME GRADUATE

Timothy Kohler, M.S. Candidate, Color Science
B.S., Printing Technology, Western Washington University, 1991.
Audrey Lester, M.S. Candidate, Color Science
B.S., Chemistry, SUNY Brockport, 1978.
Nathan Moroney, M.S. Candidate, Color Science
B.S., Color Science, Philadelphia College of Textiles and Science, 1991.
Elizabeth Pirrotta, M.S. Candidate, Color Science
B.S., Color Science, Philadelphia College of Textiles and Science, 1990.
Karen Rybarczyk, Ph.D. Candidate, Imaging Science
B.S., Physics, Canisius College, 1991.
James Shyu, M.S. Candidate, Color Science
B.S., Engineering Science, Cheng-Kung University, 1983.
M.S., Computer Science, Colorado State University, 1988.

PART-TIME GRADUATE

Jim Adams, Ph.D. Candidate, Imaging Science
B.S., Physics, Monmouth College, 1979.
B.S., Electronic Device Physics, Monmouth College, 1979.
M.S., Optics, University of Rochester, 1984.
Seth Ansell, M.S. Candidate, Color Science
B.S., Imaging Science, Rochester Institute of Technology, 1989.
Peter Burns, M.S. Candidate, Imaging Science
B.S., Electrical & Computer Engineering, Clarkson, 1974.
M.S., Electrical & Computer Engineering, Clarkson, 1977.
Cathy Daniels, M.S. Candidate, Color Science
B.S., Design and Environmental Analysis, Cornell University, 1988.
M.S., Psychology, The Pennsylvania State University, 1991.
Jack Rayhill, M.S. Candidate, Imaging Science
B.S., Chemistry, Rochester Institute of Technology, 1985.
Debbie Vent, M.S. Candidate, Imaging Science
B.S., Optics, University of Rochester, 1988.

FULL-TIME UNDERGRADUATE

Chris Hauf, B.S. Candidate, Imaging Science

Barb Grady, B.S. Candidate, Imaging Science

Daniel Smith, B.S. Candidate, Imaging Science

Funding

The Richard S. Hunter Professorship and Munsell Color Science Laboratory have 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 continues to flourish. Having state-of-the-art instrumentation makes our industrial seminars and our academic coursework much more relevant.

The following lists our non-contract supporters during the time period of this annual report. Specific projects and sources of funding are described in the next section.

ENDOWED SCHOLARSHIPS

Two endowed scholarships have been established to support graduate education in color science.

Franc Grum Memorial Scholarship

Macbeth-Engel Fellowship in Color Science

SCHOLARSHIPS

Scholarship support is difficult to quantify. Corporations may contribute direct and future funding, technical support, hardware, and Summer intern positions. The total costs for a full-time student including course work, 12 month stipend, and laboratory support are approximately $40,000 per calendar year. The following scholarships were established or continued during 1992:

Eastman Kodak Company

R.R. Donnelley & Sons, Incorporated

BASF Corporation

DuPont Imaging Systems

UNRESTRICTED RESEARCH GRANTS AND GIFTS

Elizabeth Hunter...$10,000

3M...$5,000

Miles Inc., Organic Products Division............................$2,500

Miles Inc., Industrial Chemicals Division.....................$2,000

Welch Allyn...$5,000

DEVICES

Donor	*Device*	*Value*
BYK Gardner, Incorporated	Color View Spectrophotometer	$13,000
Graseby Optronics	Autoranging Optometer	$1,400
	IEE-488 Optometer	$1,500
	Illuminance Sensor	$395
	CRT Brightness Sensor	$365
Gretag Data & Image Systems	Spectrophotometer	$12,000
Howtek, Incorporated	Scanmaster D4000	$40,000*
Huntsman Film Products	Diagonistic Materials	$500
LMT	The Photonics Directory	$80
Management Graphics	Image Recorder	$90,000*
Macbeth	Spectralight II-D75 Booth	$3,900
Milton Roy Company	Colorscans (4)	$60,000
Rolf G. Kuehni, Miles Inc.	Color: Essence & Logic Textbooks	$500
UMAX Technologies, Inc.	Color Scanner	$5,495
	Transparency Adaptor	$895

* Partial Donation

Research

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 indicates that the research was supported with the general research funds of the Munsell Color Science Laboratory. The acronym RSHP indicates 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 20-21 and 30-33 for references to more information on this research and feel free to contact any of us at the laboratory.

Color Appearance Modeling: RLAB

[MCSL]

Mark Fairchild, Roy Berns

A color appearance space, based on CIELAB, has been developed for applications in color reproduction. This space includes features to account for chromatic adaptation, cognitive effects, luminance level and surround. An article on this work will appear in *CR&A* in 1993 and it is being presented at the 1993 SPIE/IS&T Electronic Imaging meeting.

Time-Course of Chromatic Adaptation

[MCSL]

Mark Fairchild, Lisa Reniff

Previous work on this topic is being extended to provide more accurate and precise data on the time-course of chromatic adaptation to different chromaticities. This work has an impact on cross-media color reproduction studies in that it helps to define the viewing requirements for comparison of images with differing white points. Results of this study should be presented at the 1993 OSA annual meeting in Toronto.

Helmholtz-Kohlrausch Effect Modeling

[MCSL]

Mark Fairchild, Elizabeth Pirrotta, Nathan Moroney

Given high and low chroma object colors of equal luminance factor, the high chroma color will appear lighter. This phenomenon is sometimes referred to as the Helmholtz-Kohlrausch effect. Previous work on this topic was extended at the request of ISCC project committee #44. More data were collected over the past year. These data will be used by the ISCC committee and tend to verify the previous results.

Evaluation of Object Texture Using Colorimetry-Based Image Processing

[BASF, MCSL]

Seth Ansell, Roy Berns

The aim of this project is to find a color space that can be used for representing images in which it is possible to separate the visual aspects of color and texture. These analyses will aid in the formulation of textured materials and the simulation of images of these materials. During 1992, video cameras and flat-bed scanners were evaluated for colorimetric precision and accuracy. We decided on using a U-Max scanner as the input device. The remainder of the year was spent in software development and in evaluating a wedge-ring detector to reduce the amount of stored spatial information. This project is Seth's Color Science M.S. thesis.

Development of Colorimetric Plug-In Filter Modules for Adobe Photoshop®

[BASF, MCSL]

Mark Fairchild

Colorimetric image processing routines were developed for use on Apple Macintosh® computers with Adobe Photoshop®. These "plug-in filter modules" allow users to perform colorimetric conversions and manipulations on images in a very user-friendly and accurate way. This work was performed in conjunction with BASF to investigate the colorimetric image analysis of carpet fibers. An MCSL technical report that describes the use of these filters (along with the modules themselves on disk) is available.

Testing Chromatic Adaptation Transforms for Single Stimuli

[R.R. Donnelley & Sons Company, MCSL]

Elizabeth Pirrotta, Mark Fairchild, Roy Berns

Prediction of the effects of chromatic adaptation is critical in many areas of color science. This project, Elizabeth's Color Science M.S. thesis, will mathematically compare the predictions of various chromatic adaptation models for a limited set of object colors and a range of viewing conditions. Then a pair of viewing conditions will be chosen for which the models make the most different predictions. A paired-comparison visual experiment will be carried out under these conditions to derive an interval scale that quantifies the quality of the models. Elizabeth has been on leave much of 1992, but should return in 1993 to complete this work.

Testing Chromatic Adaptation Transforms for Pictorial Stimuli

[Dupont Imaging, MCSL]

Taek Kim, Roy Berns, Mark Fairchild

Taek Kim, as a Visiting Scholar from Dupont, just completed a visual experiment to test a number of chromatic adaptation models for pictorial images viewed under fluorescent daylight and incandescent illuminations at three illuminance levels. The experimental design is identical to Elizabeth Pirrotta's. Preliminary analyses indicate that von Kries based models with the exception of Nayantani's model have the best performance. Judd-type models (e.g. CIELUV) performed the poorest. An article describing the experiment in detail is in preparation.

Colorimetric Calibration of a Digital Film Recorder

[MGI, MCSL]

Roy Berns, Mike Stokes

This year we updated our film recorder to an MGI Solitaire. We have been developing software and metrology to optimize its tone reproduction characteristics and neutral tracking with a minimum of iterations and measurements. We have also begun to develop a spectral model to predict spectral transmittance from digital data based on Beer's law. Eigenvector analyses are used to define the film's spectral sensitivities and determine the amount of dye exposure. A statistical model will be optimized to relate the digital data to the amount of dye. We are hoping to write several articles on this project.

Testing Color Appearance Models for CRT-to-Print Comparisons

[Eastman Kodak Company, MCSL]

Mark Fairchild, Karen Rybarczyk

Karen Rybarczyk is in the Imaging Science Ph.D. program and is investigating the appearance of color images in different media and viewing conditions. This research will be directly applicable to the work of CIE TC 1-27. The objectives are to test various color appearance models for predicting matches between various imaging modalities. The first phase of this research, currently underway, will examine the effects of various viewing setups for the psychophysical comparison of CRT displays and prints.

Testing Color Appearance Models for CRT-to-Projected Slide Comparisons

[NSF/NYS IUCRC, MCSL]

Mark Fairchild, Audrey Lester

This project extends the work testing color appearance models to comparisons between CRT displays and projected 35mm slides. Audrey Lester will be working on this project as her Color Science M.S. thesis. Currently a special facility for the high-quality (calibrated) projection and viewing of 35 mm slides is being constructed and calibrated. In addition, direct comparisons between the projected image and a CRT display will be possible. The facilities will be completed and calibrated during 1993 and psychophysical testing should begin by the end of the year.

Color Science Education through Interactive Computer Graphics

[MCSL]

Brian Rose, Mark Fairchild

Graphics-based computer systems have provided new tools for scientists and designers that allow the manipulation of color in ways that are unfamiliar to many. Education in the fundamentals of color science, perception, and design would be very beneficial to these users. Brian Rose, for his Color Science M.S. thesis, has created an interactive computer graphics program for the Macintosh that can be used by anyone with access to a color Macintosh and an interest in color to explore fundamental concepts of color science. Brian has completed his degree and is currently employed with Apple Computer.

Sensitivity Analysis of the Hunt Color Appearance Model

[MCSL]

Chris Hauf, Mark Fairchild

This is a senior research project in Imaging Science designed to investigate the effect of variation in the various in put parameters of the Hunt model on the predicted appearance correlates. This is a numerical analysis that should lead to a better understanding of the Hunt model and, perhaps, future psychophysical experiments on the importance of viewing condition parameters.

Comparison of Color Reproduction of Various Color Print Films

[MCSL]

Barbara Grady, Mark Fairchild

This is a senior project in Imaging Science to evaluate the quality of color reproduction for three color print films: Kodak Ektar 100, Kodak Gold Plus 100, and Fujicolor Reala. The objective is to determine both overall color reproduction accuracy and to evaluate the reproduction of metameric samples. The "fourth-layer" in Reala should result in reproduction of metameric samples that correlates more closely with visual perception.

Color Difference Modeling

[RSHP]

Roy Berns

Three data bases were compiled by CIE TC 1-29: those of Luo and Rigg, Witt, and our RIT-Dupont data base. An analysis was performed to evaluate systematic and random differences between these data bases. It was found that lightness differences were dependent on viewing conditions and that the CMC lightness weighting was inconsistent with independent experiments. All three data bases showed consistent trends in chroma and hue differences that depend on the chroma location of the difference pair. A hue angle dependency that was statistically significant could not be derived. A composite color difference equation that is likely to be recommended by TC 1-29 was developed based on the three data bases.

Visual Determination of Constant Hue Loci

[Konica Corp., MCSL]

Po-Chieh Hung, Roy Berns

A visual experiment was performed using a CRT graphics display to determine loci of constant perceived hue for a wide variety of colors. The data have been analyzed in CIELAB, CIELUV, Hunt 1991, and Nayatani appearance spaces. Preliminary evaluations indicate that Hunt's space may have the best hue linearity for stimuli within CRT color gamuts. An article is in preparation for submission to *Color Research and Application*.

Investigation of Observer Metamerism

[Kollmorgen Foundation, New York State Center for Advanced Technology in Optics, MCSL]

Amy North, Mark Fairchild

This work involved the measurement of color matching functions for the determination of inter- and intra-observer variation. An article on the techniques and a second that evaluates the CIE method for predicting observer metamerism have been accepted for publication in *Color Research and Application* .

Modeling the Spectral Reflectance of a Dye-Diffusion Thermal-Transfer Printer

[RSHP]

Roy Berns

This year we finally moved beyond CRT displays as stimulus generators in our research. We have started using continuous-tone dye-diffusion thermal -transfer printers, in particular the JVC SP5501 (Dupont 4Cast) and Kodak XLT7720. We found that tristimulus empirical models based on multiple-linear regression were inadequate; as a consequence, the use of Kubelka Munk (KM) was evaluated to develop a spectral model. The model is based on the transparent form of KM and includes terms for diffusion back onto the donor supply and dye transfer inhibition. The results are equal to tetrahedral interpolation techniques. This research was presented at the AIC conference on colorant formulation and the Center for Imaging Science Industrial Associates fall meeting. An article for submission to the Journal of Electronic Imaging is nearing completion.

Generic Approach to Color Modeling

[RSHP]

Roy Berns

After teaching the coloration of textiles, polymers, and paints, and the color formation of imaging devices including photography, CRT displays, and continuous-tone printers, I found there are many commonalties. I presented the "generic" approach to color modeling at the AIC conference on colorant formulation using the JVC printer as an example. I hope to write the approach in a form suitable for publication in *Color Research and Application*.

Optimization of a Drum Scanner for Colorimetric Performance

[Dupont Imaging, Howtek, Inc.]

Roy Berns, James Schyu

For color WYSIWYG, it is necessary to colorimetrically characterize scanners for a variety of CIE illuminants. There are three approaches that can be used to accomplish this. The first is to empirically convert from scanner RGB to XYZ using multi-dimensional interpolation or multiple-linear regression. The second method is to design the scanner to have responsivities that are linear transformations of illuminant-observer color matching functions. The third method is to transform the three-channel scanner to a spectral scanner. All three methods will be compared. James Schyu will be aiding in this research and it will serve as his M.S. thesis in Color Science.

Multi-Channel Analysis of Object-Color Spectra

[Xerox, RSHP]

Debra Vent, Roy Berns

An optimization will be carried out to determine a set of channel responses for measuring object-color spectra. The optimization set will consist of the minimum number of channels, their wavelength locations, and bandwidths necessary to obtain accurate colorimetric results for illuminants D65, F2, and A when the estimated object spectra are converted to tristimulus values. This project is Debra's M.S. thesis in Imaging Science.

Spectral Matching Using Multiple Ink Sets to Minimize Metamerism

[MCSL, RSHP]

Roy Berns, Timothy Kohler

Traditional four-color printing is colorimetrically inaccurate and by definition metameric to original scenes and objects. This is an acute problem when reproducing artwork for use in high-quality texts and catalogs, as one example. This problem can be avoided if a spectral match can occur between the original artwork and its reproduction. A theoretical analysis and limited pilot experiment will be performed to evaluate the feasibility of using greater than four inks to generate spectral matches rather than colorimetric matches. To predict the spectral reflectance factor of multi-ink printing from dot areas, Neugebauer, Demichel, and Kubelka-Munk models will be employed. This project will serve as Tim's M.S. thesis in Color Science.

Gamut Mapping Psychophysics

[Konica, RSHP]

Toru Hoshino, Roy Berns

A visual experiment is underway to evaluate a number of gamut mapping techniques between rear-illuminated photographic transparencies and dye-diffusion thermal transfer reflection prints. The first set of experiments will address lightness mapping where clipping, nonlinear mapping, and linear mapping techniques will be compared for two different ranges of lightness reproduction. The second experiments will explore chroma mapping techniques. The Hunt 1991 color appearance space will be used to define each medium's color gamut. A presentation was given at the SPIE Meeting, January 1993, in San Jose, CA.

Gamut Mapping Algorithms

[MCSL]

Rab Govil, Roy Berns, Mark Fairchild

Software is under development to efficiently gamut map images within a uniform color space that will expand and compress images as needed to fully exploit a device's color gamut. Based on a set of a priori rules such as clipping or compression with constant hue or minimum color difference, images will be remapped to fill the destination gamut. The rules will be determined independently based on psychophysical experiments.

1992 Publications

The following is a list of reviewed articles and papers or abstract proceedings published or accepted for publication by faculty, staff, visiting scholars, and students of the Munsell Color Science Laboratory (listed in bold) during 1992. Past publications are listed beginning on page 26.

R.S. Berns, R. J. Motta, and M.E. Gorzynski, "CRT Colorimetry: Part I, Theory and Practice; Part II, Metrology," *Color Res. Appl.*, in press (1993).

R.S. Berns, "Color WYSIWYG: A Combination of Device Colorimetric Characterization and Appearance Modeling," *Society for Information Display Digest*, 549-552 (1992).

R.S. Berns, Book Review: "Instrumental Colour Measurements and Computer Aided Colour Matching for Textiles," *Color Res. Appl.* , **17**, 62 (1992).

M. Stokes and M. H. Brill, Note: "Efficient Computation of ΔH^*_{ab} ," *Color Res. Appl.*, **17**, 410-411 (1992).

M. D. Fairchild, Communications and Comments: "Fairchild Replies," *Color Res. Appl.*, **17**, 416-417 (1992).

M. D. Fairchild, Meeting Reports: "ISCC/TAGA 1992 Williamsburg Conference on Comparison of Color Images Presented in Different Media," *Color Res. Appl.*, **17**, 300-302 (1992).

M. Stokes, M. Fairchild, and **R. S. Berns**, "Precision Requirements for Digital Color Reproduction," *ACM Transactions on Graphics,* **11**, 406-422(1992).

M.D. Fairchild, "Quality Color Imaging Devices Poised to Enter Mass Market," *SPIE/IS&T Electronic Imaging Working Group Newsletter*, **2**, No. **4**, 2(1992).

M.D. Fairchild, "Chromatic Adaptation to Image Displays," *TAGA*, **2**, 803-824(1992).

M. Stokes, M. Fairchild, and **R. S. Berns**, "Colorimetrically Quantified Tolerances for Pictorial Images," *TAGA*, **2**, 757-778(1992).

M.D. Fairchild and P. Lennie, "Chromatic Adaptation to Natural and Artificial Illuminants," *Vision Research*, **32**, 2077-2085 (1992).

B.D. Nystrom and **M.D. Fairchild**, "Perceived Image Quality of 16:9 and 4:3 Aspect Ratio Video Displays," *Journal of Electronic Imaging,* **1**, 99-103(1992).

M.D. Fairchild, "Chromatic Adaptation and Color Constancy," *Advances in Color Vision Technical Digest*, **4** , 112-114(1992).

1992 Presentations

R.S. Berns, "Modeling Colorimetric Properties of a Dye Sublimation Printer Using Kubelka-Munk Turbid Media Theory, Industrial Associates Meeting, Rochester Institute of Technology, October.

R.S. Berns, "Color Imaging Research Applied to Art Conservation," Getty Conservation, Chicago, October.

R.S. Berns, "Color Appearance Models," Invited Presentation, Polaroid, Boston, September.

R.S. Berns, "Current Research in Color Appearance," Invited Presentation, Imaging Science and Technology Chapter, New England, September.

M.D. Fairchild, "Color Appearance Modeling," Xerox, Rochester, September.

M.D. Fairchild, "Colorimetric Digital Image Processing of Carpet Fiber Images," BASF, Enka, August.

M.D. Fairchild, "History of Technology of Color Photography," International Museum of Photography at George Eastman House, Rochester, July.

E. Pirrotta and **M.D. Fairchild**, "Testing Chromatic Adaptation Models," ISCC/AIC Conference, Princeton, June.

R.S. Berns, "A Generic Approach to Mathematically Modeling Color Systems," ISCC/AIC Conference, Princeton, June.

B. Rose, "Color Logic," ISCC/AIC Conference, Princeton, June.

R.S. Berns, "Color WYSIWYG: A Combination of Device Colorimetric Characterization and Appearance Modeling," SID Conference, May.

R.S. Berns, "Color Science: Fundamentals and Advances," Imaging Colloquia, Polytechnic University, Brooklyn, April.

M.D. Fairchild, "Chromatic Adaptation to Image Displays," Eastman Kodak, Rochester, April.

R.S. Berns, "Color Science: Fundamentals and Recent Advances," Human Factors Society, Rochester Chapter, March.

M.D. Fairchild, "Chromatic Adaptation to Image Displays," ISCC/TAGA Williamsburg Conference, February.

M. Stokes, "Colorimetrically Quantified Tolerances for Pictorial Images, ISCC/TAGA Williamsburg Conference, February.

Munsell Color Science 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.

Color Science Courses

Some minor revisions have been made in the Color Science M.S. curriculum. The order of presentation of the courses has been revised such that students can complete their course work by the end of Fall quarter of their second year and thereby begin thesis work earlier. This was accomplished by changing the Optical Radiation Measurements course from a 4 credit hour lecture and laboratory to a 2 credit hour laboratory-only course and moving it from Spring of the second year to Fall of the first year. In addition, the Theory of Color Measurement course was replaced with a new course entitled Color Appearance. The new course will include much of the same material and will appear in Spring of the first year rather than Fall of the second year. Finally, Color Science Seminar has been moved from Winter to Fall of the second year.

A proposal was also prepared for a non-thesis option in the Color Science M.S. program. It is expected that this option will attract more part-time students from local industry. This should have a positive impact on enrollment without putting undue demands on limited faculty and laboratory resources for theses. This proposal is still under review. Students enrolled in the non-thesis option will be required to complete a 1-quarter, 4-credit-hour, Color Science M.S. Project in lieu of a thesis. This project will be required to be of the same intellectual level as an M.S. thesis although less extensive. The student will then be required to fulfill the remaining credit hour requirements with professional electives. A list of the current catalog descriptions of the required courses for the M.S. in Color Science follows. The instructor's name follows the each course description in parentheses.

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. (Fairchild)

PIMC-701 3 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. (Berns)

PIMC-706 2Credit Hours APPLIED COLORIMETRY LABORATORY

Registration#0926-706

Accompanying laboratory to Applied Colorimetry. Course stresses technical writing and scientific reasoning applied in a laboratory environment. Laboratories include: spectroradiometry of natural daylight, glossimetry, visual colorimetry, color tolerance determination, and colorimetric precision and accuracy analysis of color measuring instrumentation. (Berns)

PIMC-XXX **3 Credit Hours** **COLOR APPEARANCE**

Registration#0926-XXX

This course is designed for students with an understanding of the applications of colorimetry and presents the transition from the measurement of color matches and differences to the description and measurement of color appearance. This seminar course is based mainly on review and discussion of primary references. Topics include; appearance terminology, appearance phenomena, viewing conditions, chromatic adaptation, and color appearance modeling. (Fairchild)

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. (Berns and Fairchild)

PIMC-802 **2 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. (Reniff)

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-phenomenological 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. (Berns)

PIMC-XXX **4 Credit Hours** **COLOR SCIENCE M.S. PROJECT**

Registration#0926-XXX

An independent project in an area of color science that serves as the major culminating experience for students in the non-thesis option of the Color Science M.S. program. This project can be an experiment, critical literature review, demonstration, or other appropriate work. This course requires a formal proposal and a faculty sponsor. A written technical report and oral presentation of the results are required.

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.

Industrial Courses

Short Courses

"Colorimetry: An Intensive Short Course for Scientists and Engineers" has been long running and has been well received filling its enrollment every year since its inception. Colorimetry will be offered May 11-13, 1993. The three-day course is designed to teach the effective applications of colorimetry to persons involved in coatings, textiles, polymers, reprographics, and electronic imaging. The course stressed instrumental measurements particularly useful for instrumental quality control.

As you may recall, we offered new advanced industrial courses this past summer. Unfortunately, we did not receive the anticipated number of participants. So each course objectives were reviewed and changes made accordingly. Additionally, the advertising method was adjusted to distribute two separate brochures instead of a combined brochure. The advanced courses consist of "Device-Independent Color Imaging," to be held on July 20-21, 1993; it is an in-depth short course designed to teach the theory and practice of colorimetry as applied to imaging, so called device-independent color. The other is "Quantitative Visual Evaluation of Color and Images," to be held July 22-23, 1992. This two-day course covers the quantitative evaluation of visual stimuli, known as psychophysics. Special emphasis is given to the application of psychophysical techniques to the analysis of color and images. We hope to attract more individuals interested in advanced colorimetry and psychophysics via these changes.

The Principles of Color Reproduction: An Intensive Short Course taught by Dr. R.W.G. Hunt nicely complements our Colorimetry course. We recently held this course in October of 1992. Dr. Hunt spends half of the course teaching about how color is formed using photographic, television, and reprographic imaging modalities. We have not determined the dates for 1993 although it will most likely be offered in the Fall.

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 and this past years are listed below.

Berns: "Colorimetry" section (8 hours instruction) of Imaging Science and Technology Training Program, Eastman Kodak Company, Rochester, January and February.

Berns: "Colorimetry for Electronic Imaging" (24 hours instruction): Xerox Corporation, El Segundo, California, January; Lexmark Corporation, Lexington, Kentucky, January; Xerox Corporation, East Rochester, June

Berns: "Colorimetry" section (8 hours instruction) of Color Principles for Graphics Systems oferred through IMCOTEK: Lexmark Corporation, Lexington, Kentucky, May and September; Hewlett Packard Corporation, San Diego, California; Bedford Stauffer, Bedford, Massachusetts.

Fairchild: "Vision and Color" sections (16 hours instruction) of Hybrid Imaging Technology Systems, Eastman Kodak Company, Rochester, February through March.

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.

Munsell Color Science Laboratory Plug-In Filter Modules for Adobe Photoshop, M. Fairchild, September, 1992.

Colorimetric Optimization of a NTSC Broadcast Color Video Camera, N. Katoh, August, 1992.

CRT Metrology and Colorimetric Characterization Techniques, R. Berns, M. Gorzynski, R. Motta, September, 1991.

Color Model Evaluation of a Thermal-Wax Printer, R. Luciano, May 1991.

Characterization the Colorimetric Properties of a Flat-bed Scanner Using Multiple-Linear Regression, A. North, December, 1990.

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

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

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

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

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

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

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.

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.

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

Past Publications

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

1991

M.D. Fairchild, "Formulation and Testing of an Incomplete-Chromatic-Adaptation Model," *Color Res. Appl.* **16**, 243-250 (1991).

M.D. Fairchild and **E. Pirrotta**, "Predicting the Lightness of Chromatic Object Colors Using CIELAB," *Color Res. Appl.* **16**, 385-393 (1991).

L. Reniff, "1990 Annual Meeting of the Council for Optical Radiation Measurements," *Color Res. Appl.* **16**, 64-65 (1991).

M.D. Fairchild and **L. Reniff**, "Propagation of Random Errors in Spectrophotometric Colorimetry," *Color Res. Appl.* **16**, 360-367 (1991).

Y. Liu, R.S. Berns, and Y. Shu, "An Optimization Algorithm for Designing Colored Glass Filters to Simulate CIE Illuminant D65," *Color Res. Appl.* **16**, 89-96 (1991).

R.S. Berns, "Color Tolerance Feasibility Study Comparing CRT-Generated Stimuli with an Acrylic-Lacquer Coating," *Color Res. Appl.* **16**, 232-242 (1991).

R.S. Berns, D. Alman**, L. Reniff, G. Snyder,** and **M. Balonon-Rosen**, "Visual Determination of Suprathreshold Color-Difference Tolerances Using Probit Analysis," *Color Res. Appl.* **16**, 297-316 (1991).

K.H. Parton and **R.S. Berns**, "Color modeling of Ink-jet Ink on Paper using Kubelka-Munk Theory," *Proceedings of IS&T 7th International Congress on Advanced Non-Impact Printing Technologies*, Vol 2 (1991).

P.C. Hung, "Colorimetric Calibration for Scanners and Media," *Proceedings of the SPIE Vol. 1448, Camera and Input Scanner Systems*, 164-174 (1991).

Y. Liu, "Spectral Reflectance Modification of Neugebauer Equations," *Proceedings of the Technical Association of the Graphic Arts (TAGA)*, 154-171(1991).

R.S. Berns, "Color Science Education in the 1990's," *Proceedings of the Interim Conference of the International Color Association*, in press (1991).

R.S. Berns and **M.E. Gorzynski**, "Simulating surface colors on CRT displays: the importance of cognitive clues," *Proceedings of the Interim Conference of the International Color Association*, in press (1991).

R.S. Berns, "Visual determination of color-difference vectors using probit analysis: phase II," *Proceedings of the 22nd Session of the CIE*, part I, 35-38 (1991).

R.S. Berns and **M.E. Gorzynski**, "Characterizing the total uncertainty of the colorimetric calibration of color video displays," *Proceedings of the 22nd Session of the CIE*, part I, 39-40 (1991).

M.D. Fairchild, "A Model of Chromatic Adaptation," *Proceedings of the 22nd Session of the CIE*, part I, 33-34 (1991).

1990

M.D. Fairchild, "Chromatic Adaptation and Color Appearance," *Ph.D. Dissertation, University of Rochester* (1990).

R.S. Berns and R.G. Kuehni, "What determines crossover wavelengths of metameric pairs with three crossovers?," *Color Res. Appl.* **15**, 23-28 (1990).

M.D. Fairchild, D.J.O. Daoust, J. Peterson, and **R.S. Berns**, "Absolute reflectance factor calibration for goniospectrophotometry," *Color Res. Appl.* **15**, 311-320 (1990).

M. E. Gorzynski and **R.S. Berns**, "Effects of ambient illumination and image color balance on the perception of neutral in hybrid image display systems," SPIE *Proceedings* Vol. 1250, 111-118 (1990).

M.D. Fairchild, and P. Lennie, "Spatial and temporal properties of chromatic adaptation mechanisms," proceedings of OSA Annual meeting, 149 (1990).

1989

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).

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

M.D. Fairchild and P. Lennie, "Ganglion Cell Pathways for Rod Acuity," *proceedings of OSA Annual Meeting*, 80 (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 via 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).

1987

M.D. 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).

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).

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).

1985

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

M.D. Fairchild and **F. Grum**, "Thermochromism of Ceramic Reference Tiles," *Applied Optics* **24,** 3432-3433 (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 **R.M. Miller**, "Spectrogoniophotometric Properties of Standard Reference Materials," *Mondial Couleur 85, proceedings of the 5th Congress of the International Color Association,* paper 53 (1985).

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 a facility dedicated in October of 1989 in the memory of Chester Carlson, inventor of Xerography, and that serves as a comprehensive center for education and research in imaging science. Color science is one of several major research themes of The Center for Imaging Science. The main laboratory contains many color measuring instruments and instruction area, 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. Research on color vision and image perception is performed in another laboratory located on the same floor. This laboratory contains computer systems optimized for visual display and psychophysical experimentation, and other apparatus for the study of vision. 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. The current list of equipment is given below.

Optical Properties of Materials

BYK-Gardner Colorgard System 1000 Colorimeter
0/45
Donation by BYK-Gardner

BYK-Gardner Glossgard II
20, 60 and 85 degree
Donation by BYK-Gardner

BYK-Gardner Color-view Spectrophotometer
380-720nm, 45/0, 32 diode array detector, color matching software
Donation by BYK-Gardner

BYK-Gardner The Color Sphere Spectrophotometer
380-720nm, 4d/0, 32 diode array detector,
Donation by BYK-Gardner

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

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

Cosar 75 CompuPlus Densitometer
Status A and M, transmission/reflection
Donation by Cosar Corp.

Datacolor Intl. Chroma-Sensor CS-5 Spectrophotometer
400-700 nm, d/0, interference wedge mono
Chroma-Calc color matching software for paints, textiles, and inks
Decorator 300 software
VCS-11 software
Donation by Datacolor Intl.

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

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

Gretag SPM 60 Spectrophotometer
380-700nm, 45/0, portable
Donation by Gretag

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

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

HunterLab MiniScan Spectrophotometer
Portable, 400-700nm, 45/0
Donation by Hunter Associates Laboratory

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

HunterLab UltraScan SpectroColorimeter
375-750nm , d/0, 76 diode-array detector
Donation by Hunter Associates Laboratory

IBM Model 9420 Spectrophotometer
190-900nm, transmission/reflection
Donation by IBM

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

MCSL Goniospectrophotometer
Variable illumination and viewing angles
Partally donated by Eastman Kodak Co.

Milton Roy Color Mate HDS Spectrophotometer
400-700nm, 45/0, 16 diode array detector
Donation by MiltonRoy APD

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

Milton Roy ColorScan/45 Spectrophotometer (4)
350-780nm, 45/0, grating monochromator
Donation by Milton Roy APD

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

Minolta CM-1000 Spectrophotometer
Portable, 400-700nm, d/0, diode array detector
Donation by Minolta Corp.

Minolta CM-2002 Spectrophotometer
Portable, 400-700nm, d/0, diode array detector
Donation by Minolta Corp.

Optronic 746-D Spectrophotometer
280-2500nm, 0/d, grating monochromator

Photodyne 99XL Densitometer
Portable, transmission/reflection
Donation by Photodyne

X-Rite 968 Spectrophotometer
400-700nm, 0/45, portable
Donation by X-Rite

Radiometry

Graseby Optronics UDT Photometer (2)
Autoranging, Digital, CRT sensor head
Donation by Graseby Optronics

LMT C1200 Colorimeter
17 filtered detectors, 2^{o} 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 Color Analyzer CA-100Colorimeter
4 filter, designed to measure CRT, 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 SpectraScan Spectroradiometer (2)
256 diode-array, Pritchard optical system
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

Partial List of Visual Apparatus

Breneman Visual Colorimeter
Donation by Eastman Kodak Co.

Color Curve Color Communication System
Master and gray & pastel atlases
Donation by Color Curve

Dianolite Viewing Booth (3)
D65, A, and UV
Donation by Milton Roy APD

D & H Color Rule (3)
Metameric slide rule

Datacolor International VCS-10
Maxwell disk colorimeter
Donation by Datacolor Intl.

Datacolor International Tru-Vue Viewing Booth
D65, A, CWF, and UV
Donation by Datacolor Intl.

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

Graphiclite Show-Off Portable Viewing Booth
D50, reflection and transparency viewing

ICI Color Atlas

ISCC Color Aptitude Test
Color discrimination and aptitude test

Isochromatic Plate Color Blindness Charts
Ishihara, Dvorine, and American Optical Co.

Japan Color Research Institute Chroma Cosmos 5000

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

Macbeth SpectraLight Viewing Booth(2)
D65, CWF, horizon, and narrow band fluorescent

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

Macbeth SpectraLight II Viewing Booth
D75, A, CWF, Horizon, and UV
Donation by Macbeth

MCSL Visual Colorimeter
Maxwell matching, mouse controlled

Munsell Book of Color
Glossy and matte editions
Donation by Munsell Color Company

Nagel Anomaloscope
Protan and deuteran test

Natural Color System Atlas
Donation by Swedish Standards Institute

Opthalmoscope
Donation by Welch-Allyn Inc.

OSA Uniform Color Scales

Color Display and Reproduction

Barco "Calibrator" Color Video Monitor
19V, black dot mask,
Donation by Barco Industries

HP 9000/375TSRX Computer System
HP 9000/375 host computer
graphics accelerator & processor,1280x1024x8
Donation by Hewlett-Packard

HP 98745A Color Video Monitor
Sony Trinitron, 19V
Donation by Hewlett-Packard

HP 98789 Color Video Monitor
Sony Trinitron, 16V
Donation by Hewlett-Packard

HP Paintjet Color Printer
Donation by Hewlett-Packard

Howtek 4000D Scanner
4000 dpi, drum scanner, refl. or trans.
Partial Donation by Howtek

Howtek Scanmaster Color Scanner (Sharp JX450)
300dpi, flat bed, color

Javelin JE2362 CCD Camera.
RS-170 sync, 576x485

Kodak XLT 7720 Printer
203 dpi, continuous tone, D2T2

Kodak SV-6510 Still Video Printer
Color dye-diffusion printer

Macintosh Quadra 900
Sony 16V, 24bit, 52MB RAM

Macintosh II Computer System
Sony 13V, 24 bit, 8MB RAM

Management Graphics Solitare16 Image Recorder
35mm, 4x5, 16K lines
Partial Donation by Management Graphics

Pixar II Computer System
Sun Microsystems 3/160HM, host computer,
2M Pixels x 48, 60MB RAM

Pixar II Computer System
Sun Microsystems 3/260HM, host computer,
10M Pixels x 48, 60MB RAM
Donation by R. R. Donnelley

Sharp JX-610 Scanner
600 dpi, flat bed
Donation by Sharp Corp.

Sony GDM-1950 Color Video Monitor (2)
19V, Trinitron CRT

Sony PVM-1942Q Digital Color Video Monitor
19V, Trinitron, RS-170, RGB, NTSC, PAL,
SECAM

Tektronix 650HR-C Color Video Monitor
13V, Trinitron
Donation by Tektronix

Tektronix 690SR Color Video Monitor
19V, dot mask
Donation by Eastman Kodak Co.

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

NEXTdimension Computer System
4m pixels x 32
Phillips color 17V, 1120x832x32 monitor

For More Information

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

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