Munsell Color Science Laboratory
and
Richard S. Hunter Professorship
Annual Report
1993

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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 basis. The following four basic objectives help guide their activities.

- To provide undergraduate and graduate education in color science,
- To carry on research and development in color and appearance,
- To maintain the facility to perform spectrophotometric, colorimetric, and geometric measurements at the state of the art, and
- To provide an essential ingredient for the success of the first three — namely, liaison with industry.

Ten Years In Review

Roy S. Berns, Richard S. Hunter Professor and Director, MCSL, 716-475-2230

The Richard S. Hunter Professorship and the Munsell Color Science Laboratory (MCSL) were both established in the fall of 1983. Thus, this annual report coincides with their ten-year anniversaries. I came to RIT during February of 1984 and during my first two weeks I experienced a two-foot snow storm, a heated discussion with a color photography professor about the differences between metamerism and color constancy, and the inaugural conference of the Laboratory where I was "asked" (with a 5 minute warning by Franc Grum) to moderate one of the technical sessions. This report also coincides with my ten-year anniversary at RIT. The pace and diversity of my first two weeks is representative of my first ten years. Our diversity of students, RIT colleagues engaged in color of one type or another, industries and agencies supporting our programs, and research seems unparalleled in our field. The opportunities that result from this diversity as we head into our second decade are tremendous. I would hope that if Richard Hunter, Dorothy Nickerson, Gunter Wyszecki, and Franc Grum were alive today, they would still be as excited about the Professorship and Laboratory as they were when RIT first made formal proposals to establish both endowments.

Looking back over the first decade, we experienced two complete developmental phases and entered our third phase. Our first phase was acquisitional. RIT's commitment was enthusiastic. Start-up funds were used to purchase an extensive computer system and support a graduate student, R. Mitchell Miller, whose responsibilities included systems administration and instrument repair and interfacing. A second faculty position was also established. Franc Grum, as the first Hunter Professor, used his considerable contacts and leverage to equip the Laboratory with spectrophotometers, colorimeters, vision tests, color order systems, standard reference materials, and texts and periodicals. The Hunters and former Trustees of the Munsell Foundation (most forming the first Laboratory Advisory Board) also made significant donations and helped obtain unrestricted grants to promote color science education. When I arrived in February, the Laboratory was well equipped. By 1986, industrial education was well established and a Master of Science in Color Science was promulgated by the New York State Board of Education. The generosity of the color community cannot be overstated; their unequivocal support got us up and running very quickly.

The second phase was a "show me" phase. The color community wanted to see what we would do with all the equipment and whether their trust was warranted. The success of our students in the workplace, the attendance and relevance of our industrial courses, the quality, utility, and fundability of our research, and our involvement in the color community are all metrics that can be used to evaluate whether we have "made good" on the community's initial investment. It must be noted that the early graduate students, faculty, and staff, and all of our family members were exceedingly patient and equally committed. As this second phase began, Franc Grum was killed; only through everyone's hard work and loyalty were we able to move through this critical phase. This past year seemed like a reunion from this time period. At the SPIE/IS&T San Jose conference on device-independent color imaging, I experienced my first student, Eric Walowit, presenting a seminar on colorimetry and device characterization. Ricardo Motta chaired the conference. At meetings or on site at their companies, I have seen Mike Beering, Chris Pearson, Steven Bloomberg, Mitch Balonon-Rosen, Andy Juenger, Rich Riffel, and Mark Gorzynski. They are all contributing to our field.

Several years ago, the third phase began. In this phase, our main areas of research should be defined and funded, our graduate education well established, our industrial education should be meeting current needs, we should be taking a leadership role in the color community, and we should use RIT's tremendous color resources to their full advantage. Our status concerning all of these points are described within this report. I hope you will agree that we are well into this third phase.

What of the future? At a personal level, I am interested in spectral color reproduction and colorant formulation applied to imaging. Using multi-spectral input, spectral printing models, and Kubelka-Munk turbid-media theory, more accurate color reproduction should be possible than using noncolorimetric-trichromatic input and densitometric printing models. Two recent graduates with a large positive impact on the Laboratory, Mike Stokes and Amy North, were involved at the beginning stages where we exhausted regression and benchmarked its limitations. Current students, Tim Kohler, Debra Vent, James Shyu, Peter Burns, Jim Adams, Hae-Kyung Shin, and Glenn Miller, are all contributing to our understanding of the opportunities and limitations of spectral approaches. Appearance models continue to hold my interest. When I interviewed at RIT, I presented a lecture on chromatic adaptation and color constancy based on my dissertation research. Developing a color-constant color-order system was quickly replaced with modeling electrophotography with Kubelka-Munk turbid media theory and the Neugebauer equations, the Laboratory's first research grant. Fortunately, Mark Fairchild has taken a leadership role in studying chromatic adaptation and color appearance. In our first decade, Mark has grown from a undergraduate in photographic science to a tenured professor with sufficient expertise to chair a CIE technical committee on color appearance! At RIT, we have leading programs in photography, printing, and graphic design. Our research results can be implemented and tested within a real-life context. The potential exists at RIT to make significant advances in digital-based color reproduction. Ultimately, I would like to improve the color reproduction of artwork and high-quality consumer catalogs, and use these techniques for image-based information storage and retrieval. Educationally, I would like to develop more efficient and interactive methods of teaching colorimetry and its application to the quality assurance of color materials and as a communication tool for digital imaging. Emerging multi-media may hold the key to significant educational advances.

What of the future of the Munsell Color Science Laboratory? I hope to maintain an environment where faculty, staff, students, and visiting scientists can learn and grow beyond their expectations and where they are never limited by a lack of facilities. I would also like to attract more students and scholars with interests in art, design, colorant formulation, and the quality assurance of materials.

In closing, I would like to thank the many individuals in the color community who have helped us along the way during our first decade. I sincerely hope we've earned your trust and future support as we enter our second decade. I would also like to thank my staff, Lisa and Colleen, my colleague, Mark, and my family, Susan and Abby, all of our students, and Mrs. Elizabeth Hunter for their contributions to the Hunter Professorship and the Munsell Color Science Laboratory; they have been significant.

Faculty and Staff Activities

Mark D. Fairchild, Assistant Professor, (716) 475-2784

Changes are commonplace in a university. In fact, they are what a university thrives upon. One of the most intriguing changes is the steady stream of students who join us, spend a couple of years changing themselves, and then go on to new challenges. It has been interesting to witness this progression during the last year. Early in the year two of our Color Science M.S. graduates left MCSL to move on to industrial positions. Amy North took a job in the Boston area with Iris Graphics. Mike Stokes, who also spent some time on our staff, moved on to Apple Computer in the silicon valley. It was nice for me to see both Amy and Mike again at the Color Imaging Conference this past fall in Arizona. They seem to be doing quite well in their new roles and I wish them both success. Two other students, Nathan Moroney and Elizabeth Pirrotta, are just reaching the stage of completing their degrees and will be moving on soon. Nathan recently got the final signatures on his thesis, which he also presented at the Color Imaging Conference. He is currently employed with the RIT Research Corporation. Elizabeth presented the results of her thesis over Thanksgiving and will be getting final approvals any day now. Nathan and Elizabeth have brought me a lot of satisfaction as a teacher as I have watched them change in their time at RIT. I wish them well in their future endeavors. Just as some students complete their research work, the next wave is right in the midst of battle. This is the case for two students, Karen Braun and Audrey Lester who have begun doing research with me in the past year. Karen has just obtained some very interesting results on viewing conditions for cross-media image comparisons. We will be presenting those results at the AIC meeting in Cambridge and the IS&T meeting in Rochester this coming year. As her professor, I also was honored to witness her transformation from Karen Rybarczyk to Karen Braun at her joyous wedding this past summer — congratulations. Audrey is busy on her thesis comparing CRT images with projected slides. We have made some interesting discoveries about thermochromism in slide film when it heats up in a projector that we will be presenting in the coming year. I can't wait to see what the future holds for Karen and Audrey, but I'm certain that it is promising.

A previously unpublished manuscript by Henry David Thoreau was recently published. I have had a quote from it posted outside my office door for much of 1993.

> *Though I do not believe that a plant will spring up where no seed has been, I have great faith in a seed. Convince me that you have a seed there, and I am prepared to expect wonders.*

I have been fortunate that my students have come to me with good seeds and that I have had the chance to witness the wonders. I hope I have taken good care of the seeds that were already there and maybe even planted a few new ones.

The Thoreau quote also reminds me that it has been a year of "strategic planning" for the Center for Imaging Science and RIT as a whole. I have been deeply involved in the planning process for the Center as we try to define ourselves for the difficult times the future holds and search for a new director. At this time, I am very unsure what the future will look like (perhaps only a fool is sure of the future), but I am sure that there are at least some good seeds in the Center and I am prepared to expect some wonders. All signs indicate that RIT will come out of this planning process as a very strong and revitalized university — interesting times indeed.

I taught the new Color Appearance course for the first time this past spring. This was a seminar-style course with a small number of very interested graduate students. We read historical and recent journal articles on various topics in color appearance and then discussed them for three hours each week. I enjoyed this class very much and look forward to teaching it again in 1994. My other teaching duties remained unchanged: Graduate Vision & Psychophysics, Graduate Imaging Laboratory, Graduate Color Science Seminar, and Undergraduate Vision, Color, and Psychophysics.

On the research front, I began work on a major grant from a consortium of industry, New York State, and the National Science Foundation to examine the use of color-appearance models in cross-media color reproduction. This grant will last four years with the possibility of renewal for a second four-year period. The same consortium also produced a successful proposal to New York State for designation as a Center for Advanced Technology (CAT). My part of this grant will initially go toward research on the importance of inter-observer variability in cross-media color reproduction. This grant will last five years with the possibility of renewal for another five years. I also worked on an interesting project that was funded by BASF Carpet Fibers Division in which we examined the applicability of color digital image processing to the modeling of color mixing in yarns made up of blended fibers. This joint research will continue in the coming year with a project examining the perceptual scaling of the appearance of carpet samples made out of blended yarns.

On a more personal note, there was a bit of good news in the past year. As of September, 1993, I was awarded tenure. This provides me with a degree of control and security in my endeavors and I am very grateful to all who supported my application for tenure with letters of support.

I have spent a fair amount of time this past year becoming familiar with more of the current computer technology that is available. Much of this technology will provide opportunities for color science research and education that were not feasible only a few years ago. My most recent addition has been a Silicon Graphics Indigo workstation that I plan to spend much of the coming year programming. Among other things, it will provide the graphics capabilities for some of my planned research on image manipulation and the ability to present different images to each eye through a stereo viewing option. Exploring these possibilities should be great fun. Along similar lines, I have been part of a college-wide Multi-Media Advisory committee that will recommend a strategy for multi-media education. This work has opened my eyes to some new possibilities that might be usefully applied to color science education. Stay tuned.

Finally, I want to acknowledge that I could not have possibly done everything that I have in the last year by myself. Obviously, students are a big part of my life and I thank all of them for deciding to spend some time with us at MCSL. Also despite all of the changes around a university, we have been very fortunate to have several constants; I am very grateful to Colleen Desimone, Lisa Reniff, and Roy Berns for all of the guidance, support, and assistance they have provided me. Lastly, thank you to all who have supported the laboratory, financially or otherwise, over the past year.

Lisa Reniff, Color Scientist, (716) 475-7188

As the Munsell Color Science Laboratory had it's tenth anniversary this past year, I realized I have been on staff for half of that time providing support to the faculty and students and performing research. For the first time this year my responsibilities were expanded to include teaching. I had six hard-working students for a two-credit laboratory course, Optical Radiation Measurements. If any one has taken a lab class, you know how much work a two credit hour lab would be. This was a learning experience for both me and my students. While they were learning all about how spectrophotometers worked, I learned how much time it takes to teach and how grumpy students can get before a test.

This past fall I was also lucky enough to attend the IS&T/SID Color Imaging Conference in Phoenix. It was very interesting to hear the status of research in this emerging area and the different philosophies on how and if we want to achieve accurate color reproduction. Also it was nice to visit Arizona in November. In recent research activity, the work Mark and I performed on the time course of chromatic adaptation was presented at OSA in Toronto and we are working on an accompanying paper. In addition, a paper I wrote on the transfer of the photometric scale for the calibration of reflectance materials was accepted in CR&A. Although my thesis on industrial size color differences is long gone

and collecting dust on the shelves, it keeps coming back to haunt me. This fall I helped compile the digital database of the visual results in cooperation with Dave Alman's CIE committee work. Roy is in the process of trying to gain support for a consortium on color difference research. Someday I hope to revisit this area of research and delve into the parameters that affect the perception of color difference. At the moment I'm in the midst of fixing computers gone bad.

Toru Tanaka, Fuji Xerox - Visiting Scientist

It has been almost four years since I came to Rochester in July of 1990. I've gotten used to the winters in Rochester. During the first three years, I worked for Xerox Webster Research Center. Since June of 1993, I have been studying Color Science here at RIT as a Visiting Scientist from Fuji Xerox, too. I am really enjoying this opportunity to study at RIT's Center for Imaging Science, Munsell Color Science Laboratory.

In Japan, I was in charge of Digital Full Color Xerography area. Now, here at MCSL, lectures and labs are new, interesting and useful for me. Since I am very interested in projected color image on the screen, I will study color appearance models for those projected images during the next six months.

I would like to absorb any kinds of knowledge that the color science field has to offer as well as contribute to the lab through my research.

Heui-Keun Choh, Samsung Advanced Institute of Technology- Visiting Scientist

It is easy to remember the last hot summer including Indian summer in Rochester, because it was so hot and sun light was so intense that I could not keep my skin from burning. I worried about my fovea and I bought sunglasses for the first time. But whenever I talk about the weather with somebody, they never forget to mention "the great winter in Rochester". I experienced it a little bit, already.

For the last four months I spent most of my time in making reports and performing experiments for four classes: Vision & Psychophysics, Vision & Psychophysics Lab, Optical Radiation Measurements, and Color Science Seminar. They were really helpful for me to understand the fundamentals of color science and to prepare for my further work for color appearance modeling.

I have been helped a great deal by many competent and kind people including faculty, staff, other visiting scientists and students in MCSL. It will be my great pleasure if I can help those people in any way. I do hope I can contribute to enhance the faithful relationship between MCSL and SAIT with the knowledge and experiences from MCSL.

Atsushi Suzuki, Konica Corporation -Visiting Scientist

Rochester Winter is beginning to show us it's true nature. I have spent the last eight months preparing to study color science and do my research. I work with many kind and competent people in the Munsell Lab. My principal interest concerns how humans perceive color in complex scenes. It is a very confusing and complex topic, however, I believe it is one of the most important fields of study in the imaging industry. Therefore, improving and extending current color appearance models is my task. On the other hand, I do not yet have all of the skills required to do this work and there are many fascinating distractions that life in this country offers. This is somewhat of a conflict. Anyhow, winter is the best season for doing research as I am able to avoid my temptation to play golf. Accordingly, I will utilize this winter to make this year meaningful for me.

Students

FULL TIME GRADUATE

Richard Alfvin, M.S. Candidate, Color Science
B.F.A., Photography, Rochester Institute of Technology, 1993.
Thesis Topic: TBD

Karen Braun, Ph.D. Candidate, Imaging Science
B.S., Physics, Canisius College, 1991.
Thesis Topic: Color-Appearance Modeling in Cross-Media Color Reproduction

Tim Kohler, M.S. Candidate, Color Science
B.S., Printing Technology, Western Washington University, 1991.
Thesis Topic: Reducing Metamerism and Increasing Gamut Using Five or More Colored Inks

Chris Hauf, M.S. Candidate, Color Science
B.S., Imaging Science, Rochester Institute of Technology, 1993.
Thesis Topic: TBD

Elizabeth Pirrotta, M.S. Candidate, Color Science
B.S., Color Science, Philadelphia College of Textiles and Science, 1990.
Thesis Topic: Testing Chromatic Adaptation Models Using Object Colors

Audrey Lester, M.S. Candidate, Color Science
B.S., Chemistry, SUNY Brockport, 1978.
Thesis Topic: Color Reproduction of CRT-displayed Images as Projected Transparancies

Nathan Moroney, M.S. Graduate, Color Science
B.S., Color Science, Philadelphia College of Textiles and Science, 1991.
M.S., Color Science, Rochester Institute of Technology, 1993.
Thesis Topic: Color Space Selection for JPEG Image Compression

James Shyu, M.S. Candidate, Color Science
B.S., Engineering Science, Cheng-Kung University, 1983.
M.S., Computer Science, Colorado State University, 1988.
Thesis Topic: Colorimetric Characterization of a Desktop Drum Scanner Using Spectral Models

Hae Kyung Shin, M.S. Candidate, Imaging Science
B.S., Chemistry, Ewha Womans University, 1986.
M.S., Chemistry, Ewha Womans University, 1988.
Thesis Topic: Colorimetric Characterization of a CRT-Based Film Recorder

Huanzhao Zeng, Ph.D. Candidate, Imaging Science
B.S., Physics, Hua Chiao University, 1985.
M.S., Color Science, Shandong University, 1990.
Thesis Topic: TBD

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.
Thesis Topic: TBD

Seth Ansell, M.S. Candidate, Color Science
B.S., Imaging Science, Rochester Institute of Technology, 1989.
Thesis Topic: Colorimetric and Spatial Analysis of Textured Materials

Peter Burns, Ph.D. Candidate, Imaging Science
B.S., Electrical & Computer Engineering, Clarkson, 1974.
M.S., Electrical & Computer Engineering, Clarkson, 1977.
Thesis Topic: TBD

Cathy Daniels, M.S. Candidate, Color Science
B.S., Design and Environmental Analysis, Cornell University, 1988.
M.S., Psychology, The Pennsylvania State University, 1991.
Thesis Topic: Interactive Color Image Manipulation

Glenn Miller, M.S. Candidate, Color Science
B.S., Professional Photography, Rochester Institute of Technology, 1966.
Thesis Topic: TBD

Jack Rahill, M.S. Candidate, Imaging Science
B.S., Chemistry, Rochester Institute of Technology, 1985.
Thesis Topic: Analysis of Color-Appearance Models

Debbie Vent, M.S. Candidate, Imaging Science
B.S., Optics, University of Rochester, 1988.
Thesis Topic: Multi-Channel Analysis of Object-Color Spectra

Research

Appearance Modeling and Psychophysics

One of the most significant events for MCSL color-appearance research was the publication of the RLAB color space. RLAB provides a simplified color-appearance model that appears to be both practical and successful for cross-media color reproduction applications. The model is based upon the chromatic adaptation transform previously published by Fairchild and variable exponents in the CIELAB equations to account for changes in surround.

Additional appearance-modeling research has been directed at the mathematical analysis of the models published by Hunt and Nayatani, *et al.* Chris Hauf completed an undergraduate research project in which he began a sensitivity analysis of Hunt's model in order to determine which parameters have the most significant effect on predicted color appearance. Jack Rahill is following up this work with further analysis on Hunt's model and Nayatani's model as well. Perhaps, at some point, this work will be corroborated with some visual experiments.

The other large color-appearance activity at MCSL involves testing color appearance models. This work also serves to provide data for two CIE committees active in this area. Karen Braun recently completed a preliminary study testing color-appearance models for CRT-to-print color image reproduction. This work involved the comparison of various viewing techniques to determine the most appropriate for further research. The results are fascinating and will be presented at the AIC interim meeting in Cambridge this spring. It is encouraging that the RLAB color space performed extremely well in these experiments. A short-term memory matching technique will be used in future experiments. Audrey Lester is currently involved in a similar project that will examine the comparison of CRT images with reproductions produced on projected 35mm slides.

Taek Kim completed an experiment that tested various color-appearance models for viewing printed images under different illumination conditions. This work involved comparing original prints under incandescent illumination with reproductions viewed under simulated daylight at three different illuminance levels. The results showed good performance for the CIELAB, Hunt, von Kries, and RLAB models with other models such as CIELUV, Nayatani, DuPont, and LABHNU performing significantly poorer. The results were presented at the 1993 Color Imaging Conference.

Elizabeth Pirrotta completed a similar experiment in which simple patches of object color were used rather than images. These results indicated an intriguing difference from those obtained when pictorial images were used. The Hunt color appearance model performed significantly better than all other models in these experiments. These results pointed to a problem with the RLAB that allowed it to perform very well for images, but rather poorly in some cases for simple object colors. Fortunately this problem can be solved by simplifying the model even further, which will be done at some future time.

In the course of Elizabeth Pirrotta's and Taek Kim's research, a new viewing technique for color-appearance experiments was developed — the successive-*Ganzfeld* haploscopic technique. Perhaps this technique will have some advantages for future research on color appearance. A research note was prepared on the technique and has been accepted for publication in *Color Research and Application*.

Refereed Publications

M.D. Fairchild, E. Pirrotta, and T.G. Kim, "Successive-Ganzfeld Haploscopic Viewing Technique for Color-Appearance Research," in press *Color Res. Appl.* (1994).

M.D. Fairchild and R.S. Berns, "Image Color Appearance Specification through Extension of CIELAB," *Color Res. Appl.* **18**, 178-190(1993).

Proceedings and Presentations

T.G. Kim, R.S. Berns, and M.D. Fairchild, "A Comparison of Color Appearance Models Using Pictorial Hardcopy Images," *IS&T/SID Color Imaging Conference,* Scottsdale 72-77(1993).

M.D. Fairchild and R.S. Berns, "Color Appearance Specification for Cross-Media Color Reproduction," *proceedings AIC Colour 93,* Vol. B, C11-1-C11-5(1993).

M.D. Fairchild, "RLAB: A Color Appearance Space for Color Reproduction," *Device Independent Color Imaging and Imaging Systems Integration, Proc. SPIE 1909,* 19-30(1993).

M.D. Fairchild, "Chromatic Adaptation in Hard-Copy / Soft-Copy Comparisons," *Color Hard Copy and Graphic Arts II, Proc. SPIE 1912,* 47-61(1993).

R.S. Berns, "Device Independent Color Imaging," IS&T Rochester Chapter Invited Presentation, Rochester, April.

R.S. Berns, "Current Research in Scanner, Display, and Printer Colorimetry; and Visual Appearance Modeling," Apple Computer Inc., January.

R.S. Berns, "Current Research in Scanner, Display, and Printer Colorimetry; and Visual Appearance Modeling," National Institute for Standards and Technology, January.

Technical Liason

CIE TC1-27, Specification of Colour Appearance for Reflective Media and Self-Luminous Display Comparisons, Mark D. Fairchild, Member, Roy S. Berns, Ex-Officio.

CIE TC1-32, Prediction of Corresponding Colours, Roy S. Berns, Member.

CIE TC1-34, Testing Colour-Appearance Models, Mark D. Fairchild, Chair.

Fundamental Science

The results of Amy North's M.S. thesis research on measuring color matching functions and the assessment of observer metamerism were published in a two-part *Color Research and Application* article in 1993. These papers described a technique for measuring color matching functions and provided data for a large number of replicate measurements on a single observer and single measurements for a number of observers. The results are quite enlightening and prompted some enthusiastic responses. Mark Fairchild described them and their impact on recently published work at an ISCC project committee meeting during the 1993 Newport meeting. The papers have also prompted a letter to the editor from Nayatani expressing his disagreement with the results and the conclusions that the CIE Standard Deviate Observer might be underestimating the true level of observer variability. A response to the Nayatani letter is being prepared. On a positive note, the CIE is recommending that the magnitude of the Standard Deviate Observer values be reformulated and a revision of Publication 80 be issued. In addition, Danny Rich of Datacolor International submitted an article to *Color Research and Application* that will describe some corroborating data. Additional related data will be collected at MCSL through a project supported by the recently awarded Center for Advanced Technology grant. This work will examine the magnitude of observer metamerism for color reproduction media and evaluate the results in terms of a variety of color matching functions.

On a related topic, Mark Fairchild published a Color Forum discussing recent misconceptions regarding the validity of CIE color matching functions and their practical application. This article concluded that the 1931 CIE Standard Colorimetric Observer was alive and well as neared the age of 65. The response to this article has been overwhelmingly positive with the exception of the response that was published along with it.

Much of the controversy that led to the Color Forum article also led to a CIE Symposium on Advanced Colorimetry held in the summer of 1993. Roy Berns presented a paper on the mathematical assumptions on which CIE colorimetry are based. Fortunately, this symposium appears to have put to rest unwarranted attacks on the validity of colorimetry and resulted in some progress. The future holds a system of colorimetry directly based on fundamental color matching functions, including the actions of the rod photoreceptors, and with accurate measures of observer variability. Roy Berns is chairing a new CIE committee that will try to develop a system that incorporates rod intrusion.

Another study was completed to accurately measure the time-course of sensory chromatic adaptation. This work was necessary to help in the design of color-appearance experiments in which it is necessary to be sure that the observers have been given enough adaptation time prior to beginning judgments. The results indicate that the majority of sensory chromatic adaptation at constant luminance is complete after about one minute and that this time-course is independent of the adapting-chromaticity change. These results were presented at the 1993 Optical Society of America annual meeting in Toronto by Mark Fairchild and Lisa Reniff. A paper was also submitted to JOSA on this work and a revised version will be resubmitted to JOSA in the coming year. The results have proved to be invaluable in MCSL color-appearance research.

Deb Vent is completing an M.S. thesis that is addressing a fundamental question regarding the reconstruction of spectral reflectance curves. This work is a mathematical optimization to find the minimum number of sensor responsivities and their spectral characteristics necessary to accurately reproduce spectral reflectances. This work should have some practical application for the design of multispectral sensors, image scanners, and abridged spectrophotometers.

Refereed Publications

A.D. North and M.D. Fairchild, "Measuring Color Matching Functions Part I," *Color Res. Appl.* **18**, 155-162(1993).

A.D. North and M.D. Fairchild, "Measuring Color Matching Functions Part II: New Data for Assessing Observer Metamerism," *Color Res. Appl.* **18**, 163-170(1993).

M.D. Fairchild, "Color Forum: The CIE 1931 Standard Colorimetric Observer: Mandatory Retirement at Age 65?," *Color Res. Appl.* **18**, 129-134(1993).

Proceedings and Presentations

M.D. Fairchild and L. Reniff, "Time-Course of Chromatic Adaptation," *OSA Annual Meeting Technical Digest, 1993 (*Optical Society of America, Washington, D.C., 1993) Vol. 16 p. 253.

R.S. Berns, "Mathematics of CIE colorimetry," *proceedings Advanced Colorimetry, CIE publication No. X007*, 7-17 (1993).

M.D. Fairchild, "RIT 2° Color Matching Data: Quantifying Observer Metamerism," ISCC Annual Meeting, PC#49, Newport (1993).

M.D. Fairchild, "Chromatic Adaptation in Hard-Copy / Soft-Copy Comparisons," *Color Hard Copy and Graphic Arts II, Proc. SPIE* 1912 47-61(1993).

Technical Liason

CIE TC1-43, Rod Intrusion in Metameric Color Matches, Roy S. Berns, Chair.

ISCC Interest Group #I, Basic and Applied Color Research, Mark D. Fairchild, Chair.

OSA Delegate to ISCC, Mark D. Fairchild.

ASTM E-12, Roy S. Berns, Member.

Measurement and Formulation

We have remained active providing industry with 45/0 reflectance factor calibration of BCRA Series II tiles and user-supplied materials. An article by Lisa Reniff was accepted summarizing the methods we use to transfer this scale. A second article is in preparation quantifying the effects of photometric and wavelength scale errors on colorimetric accuracy expressed in CIELAB and a simple method of spectrophotometric quality assurance. These calculations will be used in a CIE technical report of TC2-28.

Our efforts in CRT metrology by Mark Gorzynski, Ricardo Motta, and Roy Berns were published where we evaluated colorimeter and spectroradiometer precision and accuracy requirements and spatial, temporal, and additivity properties of typical computer-controlled CRT displays. Some of these results are being used by the CIE and ASTM.

Traditional computer-colorant formulation is an integral part of our research in color reproduction. However, rather than a single color, each pixel of an image may be "formulated." Single-constant Kubelka-Munk theory (transparent colorant layer over an opaque support) was used to model the spectral properties of a dye-diffusion thermal transfer printer and Dupont Cromalin. We gained insight about the importance of curve shape consistency rather than concentration linearity, ways to model colorant interaction, and limitations of the Newton-Raphson method using colorants with poor independence. This was published by Roy Berns. This insight can be applied to traditional formulation where colorants in mixture behave differently than the single colorants used to build the data base, convergence problems in ink formulation where excess ink mixtures are treated as unique inks, and formulation problems of dark colors due to measurement limitations of small-aperture instruments.

Color difference equations are an important part of color measurement. Our activities in this regard have been through CIE committee activities. The $\Delta E_{TC1\text{-}29}$ equation was developed by Roy Berns and described at AIC and ISCC conferences. It is planned to continue visual research of color tolerances through the establishment of a color difference consortium and model development from fundamental tristimulus values.

Refereed Publications

L.A. Reniff, "Transferring the 45/0 Spectral Reflectance Factor Scale," in press *Color Res. Appl. (*1994).

R.S. Berns, "Spectral Modeling of a Dye Diffusion Thermal Transfer Printer, " *J. Electronic Imaging* **2**, 359-370 (1993).

R.S. Berns, M.E. Gorzynski, and R.J. Motta, "CRT Colorimetry, Part II: Metrology," *Color Res. Appl.* **18**, 315-325 (1993).

Proceedings and Presentations

R.S. Berns, "The Mathematical Development of CIE TC 1-29 Proposed Color Difference Equation: CIELCH," *proceedings AIC Colour 93*, Vol. B, C19-1-C19-4 (1993).

R.S. Berns, "Synopsis of Roundtable Discussion on Colorimetry in Industry," *proceedings AIC Colour 93*, Vol. A, R03-01-R03-03 (1993).

D. Alman, R.S. Berns, "Why Not CMC?," ISCC Annual Meeting, Newport, RI, April.

T. Kohler and R.S. Berns, "Reducing Metamerism and Increasing Gamut Using Five or More Colored Inks," *Proceedings of IS&T Third Technical Symposium on Prepress, Proofing,* 24-28(1993).

T. Kohler, " A Method of Reducing Metamerism and Increasing Gamut of Halftone Printing through the Use of Five or More Colored Inks," Conservation Imaging Consortium Semiannual Meeting, Rochester, May.

T. Kohler and R.S. Berns, "A Method of Reducing Metamerism and Increasing Gamut of Halftone Printing through the Use of Five or More Colored Inks," ISCC Annual Meeting, Newport, RI, April.

Technical Reports

MCSL Apple Macintosh-Gretag Spectrophotometer Software Interface, M. Stokes, January 1993.

Technical Liaison

CIE TC1-28, Parameters Affecting Colour Difference Evaluation, Roy S. Berns, Member.

CIE TC1-29, Industrial Color Difference Evaluation, Roy S. Berns, Member.

CIE TC2-11, Gonioreflectometry of Standard Materials, Roy S. Berns, Member.

CIE TC2-26, Measurement of Color Self-Luminous Displays, Roy S. Berns, Chair.

CIE TC2-28, Methods of Characterizing Spectrophotometers, Roy S. Berns, Member.

ASTM E12, Roy S. Berns, Member.

Image Reproduction Colorimetry continues to play as a critical role in improving the color reproduction quality of digital color imaging devices. We have taken a two-step approach to the problem: device-colorimetric characterization followed by the use of color appearance spaces for image manipulation. This has been described in a number of publications by Mark Fairchild and Roy Berns.

Our activities in characterization are oriented towards spectral modeling. Research on CRT colorimetry carried out by Ricardo Motta, Mark Gorzynski, and Roy Berns has culminated in an article and CIE and ASTM guides that are nearing completion; the relationship between digital counts and spectral radiance was established along with practical methods of characterization. We are in the second year of a project to characterize desk-top drum scanners. This project is Jim Shyu's thesis topic. The most successful method to date treats the scanner as an imaging densitometer; the densitometric values are related to a medium's characteristic eigenvectors' principal components by a transformation matrix. The eigenvectors are based on a transformation of either reflectance factor or transmittance where only three vectors are necessary to describe the variance; for transmission media, Beer's law is used while Kubelka-Munk is used for reflection media. A similar approach was used to characterize a dye-diffusion thermal transfer printer. Beer's law is also the basis to improve the color accuracy of a MGI Solitaire 8XP CRT-based image recorder. The film recorder is treated as a sensitometer and spectral and interimage models are used to unbuild the film. This is the subject of Hae-Kyung Shin's thesis and ties in with Audrey Lester's visual experiment comparing CRT and projected slides. Finally, a multi-ink printing project was performed by Tim Kohler where a spectral image was used as input to a separation algorithm that selected 3 inks from a database of 9 inks based on minimizing illuminant metamerism between the printed reproduction and the original image. A spectral Neugebauer model with empirical dot gain functions was used. Samples were generated using hand-toned Dupont Chromalin.

Many trichromatic imaging systems (color photography, still video, broadcast television) are inherently noncolorimetric due to engineering limitations. We have begun research to develop spectral or abridged spectral (6 channel) image capture hardware as input to colorimetric based imaging systems. We are evaluating channel location and bandwidth based on a nonlinear optimization where the objective function minimizes colorimetric error under D65, A, and F2, channel noise, and the use of B&W negative film as the recording medium coupled with a drum scanner for digitization. Research in this area is being carried out by Debra Vent, Peter Burns, Glenn Miller, Lisa Reniff, and Roy Berns. A pilot experiment was performed reproducing a Macbeth color checker and oil painting by Mark Gottsegen; this was presented at the ISCC annual meeting in Newport. The colorimetric accuracy was greatly improved at the expense of increased image noise. A large and colorful painting is on loan from Wade Thompson for this project.

Several projects are addressing image manipulation. Nathan Moroney completed his thesis where several color spaces were visually evaluated for use in JPEG image compression; opponent-type spaces were significantly better than RGB or XYZ spaces. Toru Hoshino studied gamut mapping algorithms using Hunt's appearance model between back-illuminated transparencies and prints; observers preferred linear lightness and chroma clipping mapping.

Finally, we are combining traditional image processing with colorimetry in order to study methods to digitally separate color and texture. Colorimetric scanning, principal component analysis in CIELAB, and fourier analysis are the main tools. We hope to develop texture libraries and methods that can synthetically "recolor" textured materials in a realistic fashion. This will be useful for computer-aided design and color difference visual experiments studying the parametric effect of texture. Several aspects of this research are being carried out by Seth Ansell as his thesis topic.

Refereed Publications

R.S. Berns, "Spectral Modeling of a Dye Diffusion Thermal Transfer Printer, " *J. Electronic Imaging*, **2**, 359-370 (1993).

R.S. Berns, R.J. Motta, and M.E. Gorzynski, "CRT Colorimetry, Part I: Theory and Practice" *Color Res. Appl.* **18**, 299-314 (1993).

M.D. Fairchild and R.S. Berns, "Image Color Appearance Specification through Extension of CIELAB," *Color Res. Appl.* **18**,178-190(1993).

Proceedings and Presentations

N. Moroney and M.D. Fairchild, "Color Space Selection for JPEG Image Compression," IS&T/SID Color Imaging Conference, Scottsdale 157-159(1993).

T. Kohler and R.S. Berns, "Reducing Metamerism and Increasing Gamut Using Five or More Colored Inks," *Proceedings of IS&T Third Technical Symposium on Prepress, Proofing,* 24-28(1993).

T. Hoshino and R.S. Berns, "Color Gamut Mapping Techniques for Color Hard Copy Images," *Proceedings of the SPIE, vol. 1909* 152-165 (1993).

N. Moroney, "Color Space Selection for JPEG Image Compression," Conservation Imaging Consortium Semiannual Meeting, Rochester, May.

T. Kohler, " A Method of Reducing Metamerism and Increasing Gamut of Halftone Printing through the Use of Five or More Colored Inks," Conservation Imaging Consortium Semiannual Meeting, Rochester, May.

T. Kohler and R.S. Berns, "A Method of Reducing Metamerism and Increasing Gamut of Halftone Printing through the Use of Five or More Colored Inks," ISCC Annual Meeting, Newport, RI, April.

N. Moroney and M.D. Fairchild, "Color Space Selection for JPEG Image Compression," ISCC Annual Meeting, Newport, RI, April.

R.S. Berns, "Current Research in Scanner, Display, and Printer Colorimetry; and Visual Appearance Modeling," Apple Computer Inc., January.

R.S. Berns, "Current Research in Scanner, Display, and Printer Colorimetry; and Visual Appearance Modeling," National Institute for Standards and Technology, January.

R.S. Berns and L.A. Reniff, "Accurate Art Reproduction: A Not-Too Distant Reality," poster presentation, ISCC Annual Meeting, April.

Technical Reports

A Simple Printer Calibration Technique for "Good Enough" Color Reproduction of CRT Images, M. Fairchild, January 1994.

Colorimetric Characterization of the Solitaire 16 Film Recorder for Kodak Ektachrome Plus Professional 100: A Pilot Study, R. Berns, May 1993.

Spectral Modeling of a Dye Diffusion Thermal Transfer Printer, R. Berns, May 1993.

Colorimetric Characterization of Sharp JX610 Desktop Scanner, R. Berns, April 1993.

Technical Liason

CIE TC2-26, Measurement of Color Self-Luminous Displays, Roy S. Berns, Chair.

ASTM E-12.06 Appearance of Displays, Roy S. Berns, Member.

SID 1994 Annual Meeting, Mark D. Fairchild, Device-Independent Color Imaging Session Co-Chair.

IS&T/SID 1994 Color Imaging Conference, Mark D. Fairchild, Technical Co-Chair.

SPIE/IS&T 1993 Device-Independent Color Imaging and Imaging Systems Integration Conference, Roy S. Berns, Co-Chair.

Funding

Funding of our programs stems from university support in the form of faculty salaries, benefits, TA support, and physical plant; endowment earnings from the Hunter Professorship, Munsell Color Science Laboratory, Grum Scholarship, and Macbeth-Engel Fellowship; overhead recovery and income from industrial education; unrestricted research scholarships, grants and gifts; measurement services; visiting scientists; the Center for Imaging Science Industrial Associates program; restricted research grants; and equipment donations.

ENDOWED SCHOLARSHIPS

Franc Grum Memorial Scholarship

Macbeth-Engel Fellowship in Color Science

VISITING SCIENTISTS

Fuji-Xerox

Konica Corporation

NEC

Samsung Advanced Institue of Technology

UNRESTRICTED RESEARCH SCHOLARSHIPS, GRANTS, AND GIFTS

Elizabeth Hunter.....$10,000

BASF.....$25,000

Dupont.....$40,000

Eastman Kodak Company.....$40,000

Polaroid Corporation, Imaging Science Laboratory.....$5,000

Welch Allyn.....$5,000

RESTRICTED RESEARCH GRANTS

NYS-NSF/IUCRC in Electronic Imaging Systems (1992 - 1996)
Approximately $95,000 per year for the study of the application of color appearance models to various forms of cross-media color image reproduction.

NYSSTF-CAT in Electronic Imaging Systems (1993 - 1998)
Approximately $50,000 per year (dependent on industrial matching) for the studying the importance of observer variability in cross-media color image reproduction.

EQUIPMENT DONATIONS

Donor	*Device*	*Value*
ACS Datacolor International	Spectroflash500 Spectrophotometer	$22,500
BYK Gardner	Color-View Software	$1,200
George Gardner (Individual)	Color Photography Library	$1,350
Hewlett Packard	HP9000 Upgrade	$10,000
Laurin Publishing Co., Inc.	Photonics Directory	$100
LMT Germany	Digital Luminance Meter L 1009	$14,900
Macbeth	Optiview Plus Software	$6,000
	TR1224 Densitometer	$3,595
	Color-Eye7000 & 2145 Spectrophotometer & Software	$32,720

Color Science M.S. Curriculum

Enrollment in the Color Science M.S. program has remained steady over the past year. During 1993 there were 7 active full-time and 2 active part-time students. The changes made in the curriculum last year have been implemented during 1993. The new Color Appearance course was offered for the first time last Spring and was well received by both the students and faculty. It has helped tremendously in preparing our second-year graduate students for their research work. The new course sequence began this past fall with Lisa Reniff teaching the re-designed Optical Radiation Measurements laboratory course for the first time. The new design of this course, it's location early in the program and the enthusiastic instructor have contributed significantly to the success of our new graduate students. It is clear that the new curriculum will indeed encourage our students to begin their thesis research sooner and finish in a timely manner as was the objective of these changes.

Late this fall we received New York State approval for our proposed graduate-project option for the Color Science M.S. Program. This option is designed to attract more part-time students by replacing the research thesis requirement with a one-quarter graduate project plus additional elective courses. The graduate project will be at the same intellectual level as an M.S. thesis, but will be a shorter project. Incoming students may now choose, with permission of the Color Science M.S. Coordinator, the research-thesis option or the graduate-project option. Funded full-time students will continue to complete M.S. theses.

The typical sequence of courses for a full-time student in the Color Science M.S. program is given below. A part-time student would tend to take fewer courses each quarter by spreading the electives across one or two extra years. A student in the graduate-project option would replace the nine credit hours of Research and Thesis with four credit hours of Color Science M.S. project and an additional five credit hours of electives. A total of 45 credit hours are required.

Year 1

Fall Quarter:	JIMC 701	Vision and Psychophysics	4 credit hours
	JIMC 811	Optical Radiation Measurements	2 credit hours
	JIMC 890	Research and Thesis	1 credit hour
		Electives	varies
Winter Quarter:	JIMC 702	Applied Colorimetry	3 credit hours
	JIMC 712	Applied Colorimetry Lab	2 credit hours
	JIMC 890	Research and Thesis	1 credit hour
		Electives	varies
Spring Quarter:	JIMC 703	Color Appearance	3 credit hours
	JIMC 813	Color Modeling	4 credit hours
	JIMC 890	Research and Thesis	1 credit hour
		Electives	varies

Year 2

Fall Quarter:	JIMC 801	Color Science Seminar	3 credit hours
	JIMC 890	Research and Thesis	2 credit hours
Winter Quarter:	JIMC 890	Research and Thesis	2 credit hours
Spring Quarter:	JIMC 890	Research and Thesis	2 credit hours

Industrial Courses

Colorimetry - May 11-13, 1993
This three-day course presented the fundamental information necessary to make effective use of colorimetric instrumentation, theory, and practice for industries including coatings, textiles, polymers, reprographics, and electronic imaging. This course has been discontinued for 1994.

- Instructors: Drs. Roy Berns and Mark Fairchild
- 26 participants

Device Independent Color Imaging - July 20-21, 1993
This course was concerned with the theory and practice of colorimetry as applied to imaging, so called device-independent color. It included lectures and demonstrations using a Macintosh-based full-color imaging systems. Models and empirical methods were presented along with the use of color analyzers, spectroradiometers, and spectrophotometers for device characterization . This course will be extended to three days in 1994.

- Instructor: Dr. Roy Berns
- 17 participants

Quantitative Visual Evaluation of Color and Images - July 22-23, 1993
This course dealt with the quantitative evaluation of visual stimuli, know as psychophysics. Special emphasis was given to the application of psychophysical techniques to the analysis of color and images. This type of analysis is important for those working on or with systems that are intended to produce or reproduce colored stimuli or color images. The design of psychophysical experiments and the statistical analysis of the experimental results through lectures, demonstrations and laboratory exercises were presented.

- Instructor: Dr. Mark Fairchild
- 17 participants

1994 SCHEDULED SHORT COURSES

***NEW*!! Principles of Industrial Color Measurement - May 10-12, 1994**
This new three-day course will focus on the applications of colorimetry for industrial color control. Key topics include spectrophotometry: principles, geometry selection, and methods of characterizing precision and accuracy; CIE colorimetry: derivation of colorimetry from XYZ through CIELAB and CIELUV; and tolerancing: CMC and TC1-29 equations, deriving visual tolerances from historical pass/fail data, and optimizing l:c ratios. Additional topics include: terminology, color vision, color order systems, illuminant and observer metamerism, and color TQM concepts. This course is highly beneficial to persons involved in the coloration of materials such as coatings, textiles, and polymers. The course will include a visual tolerance experiment, demonstrations of color measurement instrumentation and software, and an open laboratory evening session.

Device Independent Color Imaging - June 6-8, 1994

Quantitative Visual Evaluation of Color and Images - June 9-10, 1994

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Past Publications

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

1992

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).

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).

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.D. 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).

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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).

Technical Reports

The following list MCSL 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.

- *A Simple Printer Calibration Technique for "Good Enough" Color Reproduction of CRT Images,* M. Fairchild, January 1994.
- *Colorimetric Characterization of the Solitaire 16 Film Recorder for Kodak Ektachrome Plus Professional 100: A Pilot Study,* R. Berns, May 1993.
- *Spectral Modeling of a Dye Diffusion Thermal Transfer Printer,* R. Berns, May 1993.
- *Colorimetric Characterization of Sharp JX610 Desktop Scanner,* R. Berns, April 1993.
- *MCSL Apple Macintosh-Gretag Spectrophotometer Software Interface,* M. Stokes, January 1993.
- *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*, M. Gorzynski, August 1989.
- *Goniospectrophotometric Data for Pressed Barium Sulfate Primary Transfer Standard*, M. Fairchild and D. Daoust, October 1987.
- *Goniospectrophotometric Data for Pressed PTFE Primary Transfer Standard*, M. Fairchild and D. Daoust, October 1987.
- *Report on 21st CIE Session*, R. Berns, October 1987.
- *Investigation of the Accuracy of Array Radiometry for Measuring Pulsed Radiation Sources*, W. Farrell and M. Fairchild, July 1987.
- *Munsell Color Science Laboratory Comments on NCSL Information Manual for the Design of a Standards Laboratory*, M. 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*, M. 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*, M. Fairchild, January 1987.
- *Long-Term Calibration of a Diode-Array Radiometer*, M. Fairchild and R. Berns, May 1986.

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.

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