Munsell Color Science Laboratory
and
Richard S. Hunter Professorship
Annual Report
1994

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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.

- 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.

THE YEAR IN REVIEW

Roy S. Berns, Richard S. Hunter Professor and Director, MCSL, 716-475-2230, rsbpph@rit.edu

This year in review reports on the first year of the second decade of both the Hunter Professorship and the Munsell Color Science Laboratory. This year was filled with many highlights.

The first set of highlights concerns my friend and colleague, Mark Fairchild. During 1994 he was promoted to Associate Professor and was selected as the 1995 recipient of the Bartleson Award, given by the Colour Group of Great Britain. Both awards are much deserved and reflect Mark's dedication and achievements in color science research and education. Mark is also advising the lion's share of color-oriented graduate students. Most of our students are interested in color appearance, a research area close to Mark's heart (and expertise). It is always interesting to observe the trends in students' interests. Mark, never shy of potential controversy, has spent much of the summer along with several students, collecting observer metamerism data. It will be interesting to see whether the variances are similar to those found using the MCSL visual colorimeter.

Our staff numbers also swelled this year. Along with our permanent staff members Lisa Reniff and Colleen Desimone, six visiting scientists and one postdoctoral fellow came or left through our doors. Toru Tanaka with Fuji-Xerox and Heui-Keun Choh of Samsung SAIT completed their visits this summer following successful visual experiments. On their heels came Koichi Iino from Toppan and Kazuhiko Takemura from Fuji Photo. Ethan Montag joined us from the University of Rochester. Towards the end of the year, Bong Sun Lee joined our ranks from Samsung Aerospace. Our Konica visiting scientist, Atsushi Suzuki, is in his second year of residence. As always, resident scientists add tremendous value to our research and education and we're thankful for continued industrial support.

Our students were very color active participating extensively in the ISCC through RIT's student chapter. Professors Robert Chung and Glenn Miller have provided outstanding faculty mentoring. Having color-science-literate faculty at RIT with different expertises than Mark and mine is one of the perks of working at RIT. Everyone's enthusiasm was infectious. Karen Braun, Audrey Lester, and Jim Shyu presented excellent talks at conferences and industrial sponsors during the year. Karen continues to work on the ISCC newsletter.

This year, many of our students graduated. Debra Seitz Vent, Taek Kim, and Jason Peterson received their Imaging Science M.S. degrees. Elizabeth Pirrotta, Audrey Lester, and Jim Shyu received their Color Science M.S. degrees. All are employed! Our three Ph.D. candidates, Karen Braun, Peter Burns, and Fritz Ebner are making steady progress on their dissertations.

My personal highlight of the year was getting back into the laboratory this summer. Heui-Keun Choh and I were interested in performing a color appearance experiment where the original image was on the CRT and its reproduction was a print. In all of MCSL's visual experiments, it has been the other way around due to limitations in characterizing the colorimetry of printers with sufficient precision and accuracy. This spring, Fuji generously donated a Pictrography 3000 dye diffusion printer. I spent the first part of the summer making test targets, performing spectral measurements, developing spectral models using Kubelka-Munk theory, interaction matrices, and one-dimensional spline look-up tables, inverting the model using the Newton-Raphson method, gamut mapping, and building three-dimensional tables for multi-dimensional linear interpolation. Mr. Choh characterized the CRT display and viewing conditions. We designed our experiment and added the CRT model and RLAB color appearance model into the 3D tables. The experimental results are described elsewhere in the Annual Report. I just sent in the article manuscript to the *Journal of Electronic Imaging*, complete with full-color images. It was a great feeling to do science **and** engineering. There was the added bonus that the lab now has a 3D table that performs very acceptable color reproduction from CRT to print. Karen Braun is taking advantage of this in her research.

Another research highlight was the development of a color difference consortium. Six companies have agreed to a two year commitment to support research in color tolerance development.

Lisa Reniff and Ms. Yue Qiao, an Imaging Science M.S. candidate, will be heavily involved in the experimental phases of the research. The consortium will get off the ground January, 1995.

Elizabeth Hunter, a continual friend of RIT and color science, visited us during spring. It was great fun to show Mrs. Hunter how color imaging can enhance a student's educational experience through CD-ROM, Photo CD, data visualization, and color output. She also saw how the color quality is not always what it should be.

As always, I am grateful for the hard work of our students and staff, the many equipment donations from color measurement and imaging manufacturers, and monetary donations and grants from individuals and corporations. This year, a special thank you is given to Colleen and Lisa. They effortlessly keep MCSL operating smoothly and efficiently giving me the opportunity to pursue my research interests. My activities this summer and fall would not have been possible without their efforts.

FACULTY & STAFF ACTIVITIES

Mark D. Fairchild, Associate Professor, (716) 475-2784, mdfpph@ultb.rit.edu

Last year I wrote about how quickly things change in a university setting. That couldn't have been a more prophetic topic as in the past year I have been part of more changes than ever before. But that's what makes a university such an invigorating place to be. As usual students have come and gone through my research program. Audrey Lester completed her M.S. thesis on CRT-to-slide color reproduction and has taken a job in Rochester with Eastman Kodak. I wish Audrey all of the best. Rick Alfvin and Chris Hauf quickly filled Audrey's shoes as full-time research students. Rick is working on a thesis on observer metamerism in color reproduction media that is sure to produce some interesting results. Chris is involved in a project to implement our color appearance and color reproduction software with graphical interfaces in the Iris Explorer environment on our new Silicon Graphics (SGI) workstations. He will also be developing new gamut-mapping algorithms. I look forward to seeing Rick and Chris finish up in the coming year and move on to new endeavors. Karen Braun continues to make good progress on her Ph.D. thesis. We presented results on the evaluation of viewing conditions for cross-media image comparisons and Karen is currently getting underway in the last phases of her Ph.D. work. I also have several research projects with part-time students that have been completed, are ongoing, or are being planned. These students include: Cathy Daniels, Fritz Ebner, Sue Farnand, Brian Hawkins, and Jack Rahill. Thank you to all of my students for making the Munsell lab such an interesting and exciting place to be.

I also hired the first Post-Doctoral Fellow to become part of the Munsell Color Science Laboratory in the past year. Ethan Montag, who received his Ph.D. from U.C.-San Diego under Robert Boynton and spent some time as a post-doc at the Center for Visual Science at The University of Rochester, joined us in September. Ethan will be doing research on the visual evaluation of various techniques for gamut mapping in cross-media color reproduction as well as continuing some of his color vision research. We are looking forward to Ethan's time with the lab.

Each year at this time I try to find a general theme for the previous year. This past year it seems to be travel. Looking back, I feel like I spent a lot of time in airports. So I decided to write down all my trips to see what I do in a typical (?) year. It began with a trip to the AIC meeting in Cambridge, UK this April where I presented a paper on our tests of appearance models. Next it was on to the ISCC/DCC meeting in Detroit. Then I spent a few hours at the IS&T annual meeting in Rochester where Audrey and Karen were presenting their work. In June I went to San Jose where I gave an invited presentation on device-independent color imaging at the SID annual meeting. September rolled around and I was back in England presenting our color-appearance modeling at the John Dalton Conference in Manchester. Finally I wrapped it up with a trip to Phoenix where I gave two presentations at the IS&T/SID Color Imaging Conference. These trips combined with several other trips and presentations for research sponsors (and one vacation) made for a pretty hectic year. I think it's time to slow down a little. I apologize for having to say no to several trips that I would have loved to make, but there is only so much time.

Much of my own time in the lab has been dedicated to my addiction to computer graphics hardware (*i.e.* toys). As most of you know, much of our visual research has been carried out on the Pixar image computers that I've had in the lab since about 1988. In the past year I have begun a transition of these capabilities to more modern, flexible, and expandable SGI workstations. We now have three SGI workstations in the lab and we're busy developing software for them. Some of our first experiments using the SGI's should happen in 1995 (as well as our last using the Pixars). A key feature of the Pixars for us is their capability to display color at a resolution of 10-bits for each of the RGB channels (about 1.1 billion colors). Once we are up and running on the SGI systems, I plan to upgrade to a system capable of displaying 12-bits for each of the RGB channels (about 68.7 billion colors!!). Believe it or not, these types of displays really are necessary and useful. I truly enjoy pushing this hardware to the edge of its capabilities for our color science research and coming up with new color science ideas that wouldn't have been possible to try without such hardware.

On the administrative side of things, I became the Program Coordinator for the Imaging Science Ph.D. program. This new position brings with it a lot of challenges and responsibilities. I think I am looking forward to them. With this event, the responsibilities for coordinating the Color Science M.S. program returned to Roy.

I also received a couple of bits of good news in the past year. I received a promotion in rank to Associate Professor. Thank you to all of you who supported this promotion. During the summer, I received an exciting phone call from Robert Hunt who was informing me that I had been selected to receive the 1995 C. James Bartleson award for contributions to color science. I am very honored to be receiving this award and I am looking forward to giving the Bartleson Lecture in Williamsburg this coming February.

One of the nice parts about being in a university is that I was able to spend much of the summer working on my research at home (thanks to a PowerBook and modem). This allowed me to make an addition to our family of a baby Bernese Mountain Dog named Sierra. She has been a wonderful addition to our lives and an excited visitor to the lab. She has also helped me keep everything in perspective — dogs have a very simple philosophy of life!

Thank you to everyone who has had a part to play in my always-interesting life at the Munsell lab. I am particularly grateful to my students, without whom none of this would make any sense at all. Colleen, Lisa, Ethan, Roy, and all of our visiting scholars continue to make the Munsell lab the best place I can think of to work. Last, but not least, thank you to everyone who has supported our efforts.

Lisa Reniff, Color Scientist, (716) 475-7188, larpci@rit.edu

This year there seemed to be much change happening at RIT outside the laboratory, terms like shared governance, managed attrition and strategic plan have become common buzz words as our 2-year-new president sets into motion his ideas for change. This includes a change a little closer to home, with the appointment of Edwin Przybylowicz, previously a V.P. of research at Kodak, to the position of Director for the Center for Imaging Science, and the Center temporarily coming out of RIT's structural hierarchy to hold a position like a college. I am very excited about the future direction that the Center may now take with this strong support, and the Munsell Color Science Laboratory can only benefit from the improvements.

The laboratory has been fairly steady in it's course this past year. The receipt of the NSF and CAT grants have given us some long-term sense of security because of their length, but at the same time, of course, more research to do and equipment to care for. This year we were blessed with receiving more laboratory space in the building; (he who ends up with the most square footage wins) it is named the Konica Laboratory after a corporate founder, this room, located across the hall, will be used primarily for research. With this new addition we have shuffled some equipment around and are now using a side-room for student color imaging laboratories. DuPont donated money to buy two Apple PowerPC's which I have now set up in this room with some existing computers and peripherals. Roy should be using them heavily in his color modeling course spring quarter. On the color measurement end, both Macbeth and Datacolor have generously given us integrating sphere spectrophotometers that we use for our more accurate measurements and I am in the process of investigating their capabilities. This year a paper on 0/45 calibration procedures in the laboratory that was published in CR&A that I had written and research that Mark and I performed on the time-course of adaptation has been accepted in JOSA. I am fortunate that Roy allows me to attend 1 or 2 conferences a year. This year I attended the ISCC conference in Detroit and enjoyed seeing all the colorful people and hearing what everyone was up to.

As 1995 starts, so is the Color Difference Consortium that Roy has worked hard to put together. A handful of companies have joined together to support basic research on color differences in our laboratory. I'm excited that this is actually happening and hope to have a important role in this research in the coming years.

Colleen M. Desimone, Secretary, (716)475-7189, cmd9553@rit.edu

I can't believe it has been five years since I began working for Roy, Mark, Lisa and the students. It has been very interesting, educational, and even fun. Each year has brought with it new projects and opportunities of growth. This past year seems as though it has been the most busy for me and that's why we all decided to have me write a section in this report.

Well, it doesn't seem very long ago when we were preparing last year's annual report. This is one of the most tedious jobs because it can be difficult reflecting back on last year's projects and summarizing them. Fortunately for me, the major projects I'm involved in run in a cycle which include: new students, new visiting scientists, the annual report, and preparation for the short courses. But in between all of these projects, I am editor of the ChromaZone, handle all travel arrangements for conferences, prepare presentations and reports, oversee the budget, and handle all daily projects. Nevertheless, every year I try to handle each project more efficiently. For example, we recently purchased QuarkXpress for the preparation of our new short course brochures. I learned to use and prepared the brochures from the manual. Yes, it was time consuming, but only for the first brochure. I think this program will pay for itself. Wait until you see the brochures! Also, this past year I became very knowledgeable in handling the arrival of new visiting scientists and it seems as though I have gained the trust of many on campus with my procedure. The Munsell Lab has been very fortunate to have three new visiting scientists arrive this summer and fall to study with us.

In the year to come I look forward to more new and interesting projects and more efficient ways in which I can serve Roy, Mark, Lisa, the visiting scientists, and the students.

Ethan Montag, Post-Doctoral Fellow, (716) 475-5096, edmpci@rit.edu

B.A., Psychology, University of Pennsylvania, 1995.
M.A., Experimental Psychology, University of California, San Diego, 1986.
Ph.D., Experimental Psychology, University of California, San Diego, 1991.

My first few months in the Munsell Color Science Lab have been exciting, rewarding and even a little frustrating at the same time. Starting a new position and project at a new location can be stressful but the faculty, staff and students have helped make this transition almost painless. The lab is a friendly and inviting place, and I have felt welcome from the beginning. I have been introduced to areas of research and opportunity which were previously unknown to me and this has been a great source of motivation. The frustrating part is that it is difficult to decide where to start when there is so much to learn.

My arrival at RIT coincided with the start of the fall quarter and the Color Science Seminar. I enjoyed sitting in on the class and found it valuable as a way to learn about areas of color science that were not part of my background in visual science. I was impressed with the enthusiasm of the group and the quality of the presentations and discussions. In November I attended my first color science conference, the 2nd IS&T/SID Color Imaging Conference in Phoenix. Again this was helpful in introducing me to various aspects of color science. Most useful were the practice talks and presentations by the faculty and students at the weekly lab meetings which are as valuable to me as any class.

My main area of research (under the auspices of the NSF-NYS/IUCRC and NYSSTF-CAT Center for Electronic Imaging Systems) has to do with color-gamut mapping. This research involves evaluating known gamut-mapping techniques using psychophysical analysis and developing new techniques for evaluation. The simulation and evaluation of gamut mapping algorithms with simple images will provide a basis for developing methods for gamut mapping in real image applications. I have been "collecting" gamut-mapping techniques from the literature while at the same time thinking of new ones. I am also trying to master the computer tools I will be using for the research. I have successfully developed the basic colorimetric tools I will need for switching between color spaces. The manipulation of gamuts seems more difficult and I am starting to work on that now. The 3D rendering

program I will use to generate images is great fun and I know that if I had a computer at home, I would end up neglecting my family because of it.

My other research interests include a color appearance experiment in which subjects will name colors sampled in all directions in cone-contrast space with differing colors of background adaptation. Another short term goal is to write up the research I completed at the University of Rochester last year involving interactions between form and color.

Koichi Iino, Visiting Scientist, Toppan Printing

At Toppan Printing I have been studying the color reproduction area in printing. The approaches I have used previously were more empirical and experimental rather than theoretical. I would like to learn the theoretical base of color science, vision and psychological evaluation methods in order to apply these to color printing technology. Also, I am very interested in half-tone printing using four color inks and in color reproduction for unprintable colors.

I have spent the last four months taking classes and preparing my research. Everyone has been really helpful in confirming and improving my knowledge.

I expect these experiences at the Munsell Color Science Laboratory will be one of the most meaningful things for me.

Bong-Sun Lee, Visiting Scientist, Samsung Aerospace Industries, Ltd.

It has been about two months since I came here, Greater Rochester, with an objective of developing and implementing a color correction algorithm to improve color reproduction of digital CCD camera. I have spent most of my time doing a lot of homework, performing experiments, and especially watching a TV that always gives me not only a great fun and pleasure, but also many useful words and expressions in English.

In the future, I will be very glad if I can be of any help to the many people including faculty, staff, other visiting scientists, and students in MCSL who have helped these past months. I do hope I can get along well with this great winter in Rochester.

Kazuhiko Takemura, Fuji Photo, Visiting Scientist

Since I came to Rochester at the end of August, I have learned something new everyday. They are usually great surprises to me, but I am happy to meet with them. I completely enjoy American life!

Classes and associated laboratories in the MCSL are very helpful to deepen my knowledge. As for my research, I am now preparing some psychophysical experiments on color appearance. Thanks to the kind staff, colleagues, and the good facilities, I am convinced that I can initiate my projects successfully!

Atsushi Suzuki, Visiting Scientist, Konica Corporation

Until recently, this winter has been much warmer than that of last year. This passing winter reminds me that I have completed three-fourths of my program. My efforts over the past year can be summarized as a detailed study of differing color perception models. I have compared different hypotheses, concepts, and conditions in current color appearance models including color constancy models. I have noticed that these models are characterized by assumptions regarding the fundamental characteristics of color vision. Although some of my ideas are new to the people in the Munsell Color Science Laboratory, it is possible a change in the basic assumptions regarding color vision may produce an improved color appearance model. I am close to performing an experiment that will complete the evaluation of the ideas on which I have been working. I have received much assistance and learned much from the faculty, staff, and students here. I am hopeful that the results of my work can be of use to the Munsell Color Science Laboratory as an expression of my appreciation for their contribution to my work.

Last year many people including my best friend left the Munsell Color Science Laboratory. However, I have continued to make new friends and I feel fortunate to know them. My new friends have not had the benefit of the experience of last year's weather here, which was cold and miserable I am very interested in seeing the end results of my experiment, although when leaving, I will miss the friendly atmosphere of the lab.

FULL TIME GRADUATE STUDENTS

Richard Alfvin, M.S. Candidate, Color Science
B.F.A., Photography, Rochester Institute of Technology, 1993.
Thesis Topic: A Computational Analysis of Observer Metamerism in Cross-Media Color Matching

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

Chris Hauf, M.S. Candidate, Color Science
B.S., Imaging Science, Rochester Institute of Technology, 1993.
Thesis Topic: Device Independent Color Modules for Silicon Graphics Iris Explorer

Audrey Lester, M.S. Graduate, Color Science
B.S., Chemistry, SUNY Brockport, 1978.
M.S., Color Science, Rochester Institute of Technology, 1994.
Thesis Topic: Color Reproduction of CRT-displayed Images as Projected Transparencies

James Shyu, M.S. Graduate, Color Science
B.S., Engineering Science, Cheng-Kung University, 1983.
M.S., Computer Science, Colorado State University, 1988.
M.S., Color Science, Rochester Institute of Technology, 1994.
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

Manuel Trevisan, M.S. Candidate, Color Science
B.S., Printing, San Zeno 1992.
Thesis Topic: TBD

Yue Qiao, M.S. Candidate, Imaging Science
B.E. Materials Science and Engineering, Beijing University of Science and Technology, 1988.
M.S. Physics, John Carroll University, 1993
Thesis Topic: Color Tolerance Psychophysics

PART TIME GRADUATE STUDENTS

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

Robert Poetker, M.S. Candidate, Color Science
B.S., Computer Engineering, University of Evansville, 1983.
Project Topic: TBD

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.
Project Topic: Comparison of Print & Slide Color Reproduction

Sue Farnand, M.S. Candidate, Imaging Science
B.S., Mechanical/Agricultural Engineering, Cornell University, 1984.
Thesis Topic: Effect of Imaging Content on Color-Difference Perception

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

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

RESEARCH

Appearance Modeling and Psychophysics

A great deal of interest has been generated by the RLAB color-appearance model that was published by Fairchild and Berns in 1993. In the past year Mark Fairchild spent some time evaluating the equations that form the model and their visual significance in the light of the data that has been collected over the last couple of years. A flaw in the model that became apparent when simple stimuli were used, but was masked in complex images, was identified. A correction was made to remedy this situation. In addition the equations were simplified. The result was a simpler RLAB model that retains the same levels of performance. The revisions and their derivation were presented at the John Dalton Conference in Manchester, UK and at the 2nd Color Imaging Conference in Scottsdale. Some further equation simplifications will be made that have no numerical effect on the results and a journal article on the revised model will be submitted in 1995.

Karen Braun completed the first phase of her Ph.D. dissertation. This involved the evaluation of various viewing arrangements for visual experiments aimed at testing color-appearance models for CRT-to-print image reproduction. The results were quite interesting and indicated that the best technique is memory matching and that simultaneous viewing, which is common practice, is seriously flawed. The results were presented at the AIC interim meeting in Cambridge, UK and the IS&T annual meeting in Rochester. A paper on this research authored by Karen Braun, Mark Fairchild, and Paula Alessi of Eastman Kodak will be submitted to *Color Research and Application* very early in 1995. Along similar lines, a paper on the successive-*Ganzfeld* haploscopic viewing technique for color-appearance research by Fairchild, Pirrotta, and Kim appeared in 1994.

Audrey Lester completed her M.S. thesis that included many aspects of color science. One part was the evaluation of various color-appearance models for the reproduction of CRT-displayed images as projected 35mm slides. We are happy that this work showed that the RLAB color space performed extremely well in this situation. This work was also presented at the Color Imaging Conference.

Our industrial visiting scientists were also busy doing color-appearance research. Toru Tanaka, from Fuji-Xerox, spent a year at MCSL and completed a project looking at the application of color-appearance modeling to the production and viewing of color overhead transparencies. He found that the perceptual attributes of brightness and colorfulness better correlated with observer-preference responses than the attributes of lightness and chroma. This result was found for business graphics and pictorial images. Another interesting (but not unexpected) result was that preference decreased at very high luminances. An article is in preparation for submission to the *Journal of Electronic Imaging*.

Heui-Keun Choh, from Samsung Advanced Institute of Technology, completed two visual experiments. The first was a lightness scaling experiment using a CRT display. Using the method of adjustment, observers produced an equal-interval lightness scale under different surround conditions. The effects of surround were similar to those found historically by Breneman and Bartleson. The dim and dark surround effects were similar to one another; the dim conditions used when viewing computer graphic displays tend to be dimmer than the surround conditions typical of broadcast television. The lightness scales were typically nonlinear though not identical to any model. This result suggests that absolute scales of lightness are very dependent on experimental design.

Heui-Keun Choh and Roy Berns performed a visual experiment to determine whether the RLAB color-appearance model could be used successfully to generate reflection prints that match the appearance of a CRT when viewed under mixed states of adaptation and in turn as stand-alone images viewed under a single state of adaptation. Although not recommended, mixed adaptation often occurs; the CRT is balanced to D65 and viewed in a room with cool-white fluorescent lamplight. The RLAB color-appearance model was used to calculate corresponding images where the observer's state of chromatic adaptation was assumed to be influenced by each device to various degrees. Observers first judged the reflection prints adjacent to the CRT display selecting the image closest in color appearance to the CRT image; they also categorized the closest image as "acceptable," "marginally acceptable," or "not acceptable." The images were again scaled except the display was turned off; this determined the

best stand-alone color reproduction. The observers determined that images generated where it was assumed that the CRT adaptation was shifted 25% towards the print condition and a print adaptation was shifted 25% towards the CRT condition produced both the closest match to the CRT display and best stand-alone image. The mixed-adaptation matches were acceptable or marginally acceptable on average 84%. This adaptational condition produced the most preferred stand-alone images due to shifts towards regions of known preferred color reproduction in dim lighting. An article was submitted to the *Journal of Electronic Imaging*.

Refereed Publications

M.D. Fairchild, E. Pirrotta, and T.G. Kim, "Successive-Ganzfeld Haploscopic Viewing Technique for Color-Appearance Research," *Color Res. Appl.* **19**, 214-221(1994).

Proceedings and Presentations

M.D. Fairchild, "Visual Evaluation and Evolution of the RLAB Color Space," *IS&T/SID 2nd Color Imaging Conference,* Scottsdale, 9-13 (1994).

M.D. Fairchild, R.S. Berns, A. Lester, and H.K. Shin, "Accurate Color Reproduction of CRT-Displayed Images as Projected 35mm Slides," *IS&T/SID 2nd Color Imaging Conference,* Scottsdale, 69-73 (1994).

R.S. Berns, "Current Research In Color Appearance," *Polaroid Corporation (*1994).

M.D. Fairchild, "Predicting Color Appearance of Simple and Complex Stimuli," *Center for Imaging Science Industrial Associates Program,* Fall Meeting (1994).

M.D. Fairchild, "Predicting Color Appearance of Simple and Complex Stimuli," *The John Dalton Conference,* Manchester UK (1994).

K. Braun and M.D. Fairchild, "Viewing Environments for Cross-Media Image Comparisons," *IS&T's 47th Annual Conference/ICPS,* Rochester 391-396 (1994).

M.D. Fairchild and K. Braun, "Testing Color-Appearance Models in Cross-Media Image Reproduction," *AIC Interim Meeting: Images in Colour,* Cambridge (1994).

Technical Liaison

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.

ASTM E12.11, *Standard Guide for Designing and Conducting Visual Experiments*, Mark D. Fairchild, Author.

RESEARCH

Fundamental Science

Much of the summer of 1994 was spent collecting new data on observer metamerism. These data consist of simple-field matches made between either a photographic print or transparency under a fluorescent daylight and a CRT display. The spectral power distributions of each match were measured to allow analysis of a variety of current and future sets of color-matching functions. Rick Alfvin is analyzing the data for his M.S. thesis. Thus far we have confirmed the utility of CIE colorimetry and found good measures of observer variability. We are in the process of trying to develop an accurate technique for predicting observer variability. Rick will be presenting the results in February at the ISCC Pan-Chromatic Conference. A *Color, Research, and Application* article is also in the works.

In the course of making calibrated slides for projection, Audrey Lester, discovered that the colors of the slides change dramatically when they undergo substantial heating in the projector. This resulted in a slight detour in her thesis to explore the relationship between temperature and color in photographic transparencies. The shifts in color are visually significant and can generally be considered a loss of chroma with temperature. The results were published in the *Journal of Imaging Science and Technology* and presented at the IS&T annual meeting.

Much of the more fundamental color science work at MCSL has revolved around quantifying the performance of chromatic adaptation mechanisms. Mark Fairchild and Lisa Reniff's work on the time-course of chromatic adaptation mechanisms was accepted for publication in *J.O.S.A. A*. In the course of revising this manuscript, interesting functions that fitted the data almost perfectly were derived. These functions were sums of two exponentials. This result lends support to several theories suggesting two physiological mechanisms of chromatic adaptation. The MCSL work on chromatic adaptation also led to the development of the successive-*Ganzfeld* haploscopic viewing technique for color-appearance research published in 1994.

At the 1991 International Association of Colour interim meeting on light and colour held in Sydney, Australia, Roy Berns was asked to deliver an invited address about color science education. This address was expanded and published this year in *Color, Research, and Application* as a *Talking About Color* article.

Mark Fairchild and Lisa Reniff carried out a research project on the perception of carpet samples made up of blended fibers. This work, sponsored by BASF's Carpet Fibers Division, involved multidimensional scaling of observers' judgements of similarity and difference of carpet fibers. The results indicated that mean-color and lightness-distribution were the most important measurable factors.

Lastly, some research originally started when Mark Fairchild was at the University of Rochester in 1987, made its way into print. This work examined the relationship between the visual resolution of rod vision and anatomical estimates of ganglion-cell densities to try to define the physiological pathways for rod information. The results helped to show that the rods and cones share the same pathways. In fact, the rods are likely to contribute to color vision in some circumstances.

Refereed Publications

M.D. Fairchild and L. Reniff, "Time-Course of Chromatic Adaptation for Color-Appearance Judgements," *Journal of the Optical Society of America A* in press (1995).

A. Lester and M.D. Fairchild, "Thermochromism of Ektachrome 100 Plus Professional Transparencies Upon Projection, "*Journal of Imaging Science and Technology*, **38** , 332-338 (1994).

MD. Fairchild, E. Pirrotta, and T.G. Kim, "Successive-Ganzfeld Haploscopic Viewing Technique for Color-Appearance Research," *Color Res. Appl.*, **19**, 214-221 (1994).

R.S. Berns, "Color Science Education in the 1990's," *Color Res. Appl.*, **19**, 74-76 (1994).

P. Lennie and M.D. Fairchild, "Ganglion Cell Pathways for Rod Vision," *Vision Research*, **34**, 477-482 (1994).

Proceedings and Presentations

M.D. Fairchild, "Predicting Color Appearance of Simple and Complex Stimuli," *The John Dalton Conference*, Manchester UK (1994).

A. Lester and M.D. Fairchild, "Thermochromism of Ektachrome 100 Plus Professional Transparencies upon Projection," *IS&T's 47th Annual Conference/ICPS*, Rochester 779-782 (1994).

A. Lester, "Thermochromism of Ektachrome 100 Plus Professional Transparencies upon Projection," *ISCC Annual Meeting*, Detroit (1994).

Technical Liaison

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.

RESEARCH

Measurement and Formulation

Our main efforts in metrology have been in the area of reflection spectrophotometry. Our calibration procedures for 45/0 reflectance factor measurements were described in an article by Lisa Reniff published in *Color, Research, and Application*. Results are shown for calibrations performed over a three year time span. The average reflectance factor error consistently found between the corrected measurements of the NIST standards and their certificate values have been 0.0006 and the average ΔE^*_{ab} has been on the order of 0.2.

Roy Berns and Lisa Reniff are preparing an article for submission to *Color, Research, and Application* describing a simplified method of diagnosing spectrophotometric errors using the BCRA Series II Cyan tile. Comparing L*, a*, and b* measurements with either certificate values or values from an arbitrary point in time can be used to evaluate photometric and wavelength scale errors. This information would be very useful in indicating whether changes in an instrument's readings is due to the changes in the white transfer standard, black trap, or an internal problem associated with the dispersing element.

Our research in color differences has been focused this year on obtaining funding. A consortium on Industrial Color Difference Evaluation was formed during fall. The purpose of the research program is to improve the effectiveness of automated industrial-color difference evaluation. Specific objectives to accomplish this goal include: 1) Develop experimental data to describe the consumers' color-difference judgment behavior under a variety of industrial application conditions, 2) Develop computational models of color-difference perception with improved performance in relation to human color-difference judgments, and 3) Provide guidance to industry on the effective application of computational color-difference evaluation. The following companies have joined the Consortium: 3M, Datacolor International, Detroit Color Council, Dupont Automotive, Macbeth, and Miles Laboratory. The first meeting of the Consortium is scheduled for January, 1995.

While obtaining funding, we have not been idle. Roy Berns presented a paper on the development of the new CIE94 color difference equation at the joint Inter-Society Color Council and Detroit Color Council meeting in Detroit during April. Roy will also be collaborating with David Alman of Dupont and Professors Hita and Melgosa from the University De Granada on a more detailed analysis of the visual data collected by MCSL by Gregory Snyder and Lisa Reniff (*Color Res. Appl*. **16**, 297-316, 1991).

Integral densitometry is often used as an analytical tool to estimate the amount of dye present in a photographic film. Because the color formation principles defining the relationship between either transmittance or reflectance and dye concentration are nonlinear, densitometers ideally should have spectral responsivities of about 10 nm at half-height bandwidth. Status densitometers, common to the photographic industries, have responses of about 50 nm. Hae-Kyung Shin, as part of her master's thesis concerned with colorimetric characterization of a CRT-based film recorder, quantified the modeling errors resulting from using a status densitometer to estimate dye concentration. She found average errors of about $2\Delta E^*_{ab}$ with maximum errors approaching 4 ΔE^*_{ab}. Hae-Kyung presented these results at the Center for Imaging Science's Fall Industrial Associates Meeting.

Refereed Publications

L.A. Reniff, "Transferring the 45/0 Spectral Reflectance Factor Scale," *Color Res. Appl.,* **19**, 332-340 (1994).

Proceedings and Presentations

R.S. Berns, "The Mathematical Development Of CIE TC 1-29 Proposed Color Difference Equation," *Detroit Color Council and Inter-Society Color Council joint conference,* Detroit (1994).

H.K. Shin, "Colorimetric Characterization Of A Solitaire 8-XP CRT-Based Film Recorder Via Image Modeling And Principal Component Analysis," *Center for Imaging Science Industrial Associates Program,* Fall Meeting (1994).

Technical Liaison

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.

RESEARCH

Image Reproduction Device colorimetric characterization and color appearance modeling are the tools used at MCSL for color image reproduction. Research directly addressing color appearance has been described in a previous section. This section describes characterization research and research where we have put together imaging systems using these tools.

For the last two years Dupont's Printing and Publishing Division and Howtek have been supporting Jim Shyu's M.S. thesis on the colorimetric characterization of a Howtek D4000 drum scanner. The technique first modeled the image formation of each medium using either Beer-Bouguer or Kubelka-Munk theories. Scanner digital values were then empirically related to dye concentrations. From these estimated dye concentrations, either spectral transmittance or spectral reflectance factor was calculated from an *a priori* spectral analysis of each medium. The scanner was colorimetrically characterized to average CIELAB error of less than unity for Kodak Ektachrome transparencies and Ektacolor paper, and Fuji Photo Film Fujichrome transparencies and Fujicolor paper. Independent verification on spectrally similar materials yielded average ΔE^*_{ab} error of less than 2.1. Roy Berns and Jim presented a paper at the SID/IS&T 2nd Color Imaging Conference in Scottsdale. An article to be submitted to the *Journal of Electronic Imaging* is nearing completion.

Last year, Roy Berns published a paper describing the colorimetric characterization of a JVC dye-diffusion thermal-transfer printer (sold in the U.S. as the Dupont 4Cast). This technique was used successfully to characterize a Fuji Pictrography 3000 to average and maximum errors of 1.6 and 5.6 ΔE^*_{ab}, respectively. Roy and Heui-Keun Choh concatenated this characterization with characterizations of a CRT display and desk-top flat-bed scanner to create a system that would take Kodak Ektaprint images and reproduce them as CRT or Pictrography images. During this coming year, we plan to integrate Jim Shyu's results and add gamut mapping to the system. (We currently perform minimum ΔE^*_{ab} clipping.)

Since printer characterizations are complex and time consuming, Mark Fairchild developed a simple method that can provide "good-enough" color reproduction. The method consists of tone reproduction and a rotational color correction matrix. It was published as a MCSL technical report.

A second imaging system that was characterized was reproducing CRT images as 35mm projected slides. This was a group effort involving Audrey Lester, Hae-Kyung Shin, Mark Fairchild, and Roy Berns. Hae-Kyung's M.S. thesis dealt with predicting the spectral transmittance of the slide film from digital data. Audrey's thesis was concerned with defining the appearance of the projected slides and testing several color appearance models so that the projected slides matched the appearance of the CRT images. This has been a very difficult system to work with due to the complexities of modeling Ektachrome's inter-image effects, the film's thermochromism, gamut mapping, and problems encountered due to many appearance models predicting corresponding colors outside of the projected slide's color gamut. Mark presented a paper at the SID/IS&T 2nd Color Imaging Conference in Scottsdale.

Research continues in multi-spectral imaging. Debra Seitz-Vent completed an M.S. thesis where nonlinear optimization was used to derive a set of detector responses that estimate various material's spectral reflectance factor. The objective function minimized ΔE^*_{ab} for illuminants D_{65}, F2, and A. The detectors were gaussian and constrained within the visible spectrum. The detector peak wavelength and bandwidth were determined for 3 - 8 channels. Peter Burns has been deriving equations to estimate colorimetric noise resulting from multi-channel input. In the future, these analyses can be combined to develop a multi-spectral digital input device.

Refereed Publications

N. Moroney and M.D. Fairchild, "Color Space Selection for JPEG Image Compression," *Journal of Electronic Imaging* in press (1995).

A. Lester and M.D. Fairchild, "Thermochromism of Ektachrome 100 Plus Professional Transparencies Upon Projection," *Journal of Imaging Science and Technology*, **38**, 332-338 (1994).

Proceedings and Presentations

R.S. Berns and M.J. Shyu, "Colorimetric characterization of a desktop drum scanner via image modeling," *IS&T/SID 2nd Color Imaging Conference,* Scottsdale, 41-44 (1994).

M.D. Fairchild, R.S. Berns, A. Lester, and H.K. Shin, "Accurate Color Reproduction of CRT-Displayed Images as Projected 35mm Slides," *IS&T/SID 2nd Color Imaging Conference,* Scottsdale, 69-73 (1994).

M.D. Fairchild, "Some Hidden Requirements for Device-Independent Color Imaging," *SID International Symposium,* San Jose, 865-868 (1994).

A. Lester and M.D. Fairchild, "Thermochromism of Ektachrome 100 Plus Professional Transparencies upon Projection," *IS&T's 47th Annual Conference/ICPS,* Rochester, 779-782 (1994).

M.D. Fairchild, "Cross-Media Color Reproduction Research," *Center for Electronic Imaging Systems, Special Interest Groups,* Anniversary Meeting (1994).

M.D. Fairchild and K. Braun, "Testing Color-Appearance Models in Cross-Media Image Reproduction," *Royal Photographic Society/AIC Interim Meeting: Images in Colour,* Cambridge (1994).

R.S. Berns, "Research in colorimetric and multispectral graphic reproduction," *Center for Imaging Science Industrial Associates Program,* Fall Meeting (1994).

R.S. Berns, "Recent Advances In Colorimetry-Based Digital Imaging," *Royal Photographic Society/AIC Interim Meeting: Images in Colour,* Cambridge (1994).

R.S. Berns, "Recent Advances In Colorimetry-Based Digital Imaging," *Hewlett Packard,* San Diego (1994).

R.S. Berns, "Cross-Media Matching," in *Smart Color 94,* Stanford (1994).

Technical Reports

M.D. Fairchild, "A Simple Printer Calibration Technique for 'Good-Enough' Color Reproduction of Color Images," *MCSL Technical Report*, 1994.

Technical Liaison

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.

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 Photo Film Ltd.	Fuji Xerox	Samsung Advanced Institute of Technology
Konica Corporation	Toppan Printing	Samsung Aerospace Industries, Ltd.

Unrestricted Research Scholarships, Grants, and Gifts

Elizabeth Hunter.....$10,000

BASF.....$25,000

Dupont Imaging Systems.....$40,000

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

Polaroid Corporation, Imaging Science Laboratory.....$10,000

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	*Item Description*	*Value*
DuPont	MacIntosh Power PC 7100	$9333
Susan Farnand(individual)	Hoechst Standard Colours on Silk	$100
	1935 IPI Monographs on Color	$100
	1915 Atlas of the Munsell Color System	$500
Fuji Photo Film Co., Ltd	Pictrography Printer	$24,000
	ANSI IT8 Transmission and Reflection Color Targets	$60
Minolta Corporation	SpectraMatch Software & RGB RAM for CA-100	$370
RIT Research Corporation	Barco Chameleon Chip Software Board & Installation	$8540
Tektronix, Incorporated	J17 Photometer	$2319

COLOR SCIENCE M.S. CURRICULUM

Enrollment in the Color Science M.S. program has increased slightly over the past year. During 1994 there were 5 active full-time and 5 active part-time students. This is a decrease in our full-time enrollment and an increase in our part-time enrollment. The graduate-project option begun last year is the main reason for the increased number of part-time students. We hope to increase full-time enrollment for the 1995-1996 academic year.

The typical sequence of courses for a full-time student in the Color Science M.S. program is given below. 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 well-prepared student enrolled in the graduate-project option could complete their degree requirements in 15 months. A part-time student would tend to take fewer courses each quarter by spreading the electives across one or two extra years. 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

Previous Participation

May 10-12, 1994 **Principles of Industrial Color Measurement**

- Instructors: Drs. Roy Berns and Mark Fairchild
- 21 participants
- Some companies included: Welch Allyn, 3M, Dupont, Xerox, and PPG Industries.

June 6-8, 1994 **Device-Independent Color Imaging**

- Instructor: Dr. Roy Berns
- 9 participants
- Some companies included: Eastman Kodak Company, Hewlett Packard and NIST.

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

- Instructor: Dr. Mark Fairchild
- 10 participants
- Some companies included: Miles Inc., Honda of Canada, and Xerox.

1995 Scheduled Short Courses

June 5-7, 1995 **Principles of Industrial Color Measurement**

A three-day intensive short course designed to teach the color science principles necessary to make effective use of color measurement instrumentation. Key topics include spectrophotometry, derivation of colorimetry through CIELAB, and CIE94 and CMC color tolerance equations. The course consists of lectures, instrument demonstrations, visual experiments, and an open laboratory session. Instructed by Dr. Roy S. Berns and Dr. Mark D. Fairchild.

June 8, 1995 **Industrial Instrumental Color Matching**

This is a *Special Offer* for the coming year. A one-day intensive short course designed to help participants make more effective use of computer colorant formulation systems. Key topics include spectral analyses of colorants, color matching theory, batch correction, and getting the most out of a system. The course consists of lectures, in-class formulation hand calculations, and a problem-solving session. Instructed by Mr. Ralph A. Stanziola of Industrial Color Technology.

June 12-14, 1995 **Device-Independent Color Imaging**

A three-day, intensive short course designed to teach methods of achieving high-accuracy color for electronic imaging peripherals, so called device-independent color. Color peripherals such as scanners, CRT displays, and thermal, ink-jet, electrophotographic and direct-digital printers, are an integral part of today's document processing and publishing and scientific visualization. In order to integrate these devices and achieve acceptable color fidelity, an understanding is required of the visual system (colorimetry), metrology (spectrophotometry, photometry, spectroradiometry), image formation principles (color modeling), and the interaction between observers and the colored image (color appearance). This understanding is incorporated into color management systems providing "plug and play" capabilities. These topics will be covered in this course. After taking this course, participants should have a better understanding of methods to colorimetrically calibrate and characterize scanners, displays, and printers; build device profiles; and use these results to improve the color fidelity of these peripherals through software development and color management systems. Instructed by Dr. Roy S. Berns.

June 15-16, 1995 Color-Appearance Models: Theory & Practice

This is a ***NEW*** two-day intensive short course covering the fundamental phenomena, techniques, and models of color appearance. Color-appearance models extend basic colorimetry, as typified by CIE tristimulus values, to the prediction of color matches and color appearance across widely varying viewing conditions. Tristimulus values can only predict color matches for identical viewing conditions. Recent advances in open systems for electronic image reproduction have accented the need for accurate and efficient color-appearance models. For example, the only way to equate the colors an observer sees on a computer monitor when creating or editing an image with those that will be produced when a print is made is to use a color-appearance model. This is because the original computer display is self-luminous and typically viewed in dim surroundings while the print is reflective and viewed in light surroundings with a particular light source. Color-appearance models can account for these changes in viewing conditions while basic colorimetry cannot. Color-appearance models are also used to evaluate the color rendering of lighting to compare how colored objects will appear under various sources. Participants should have a better understanding of current color-appearance models and their application after taking this course. Instructed by Dr. Mark D. Fairchild.

For More Information Contact:

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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.

1993

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).

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

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).

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).

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).

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).

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).

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

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

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, "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*, 135-137 (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*, 21-24 (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).

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).

E. Walowit, C.J. McCarthy, 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).

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.

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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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