Munsell Color Science Laboratory
and
Richard S. Hunter Professorship
Annual Report
1995

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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

Certainly during my tenure in academia, the university is a reflection of our society. The concept of the "ivory tower" is as foreign to me as the Tower of Babel. This seems particularly true here at Munsell. MCSL has participated in several lifecycle events.

Two families have begun. Colleen Desimone is now a mother of a beautiful son, Michael James. As I am writing this Year in Review, Lisa and Mark just became parents to a beautiful daughter, Acadia. Following their maternity leaves, both Colleen and Lisa will be working on a part-time basis.

We have experienced relocation. The Center for Imaging Science has joined the College of Science leaving the College of Imaging Arts and Sciences. This will enhance our opportunities to collaborate with new faculty and students. For example, during the summer, I helped two faculty develop visual methods of defining the color of the feet of blue-footed boobys, found in the Galapagos Islands. This new organizational structure should also help in maintaining the color science program's wide breadth.

We have performed our community service. Mark and I continue to chair CIE technical committees. We have both learned through firsthand experiences the inter-relationships between technical and political issues. Mark serves on the ISCC Board of Directors and is involved in the technical program of the yearly color imaging conference in Scottsdale, Arizona. I wrote three overview articles about colorimetry and the color science program.

We have a "sister" community, the Pacific rim. Four visiting scientists were in residence, three from Japan and one from Korea. In addition to science, we are sharing our cultures, in particular food! I have been writing articles with current and past visiting scientists. An article on hue scaling appeared in *Color, Research, and Application* co-authored by Po-Chieh Hung and myself. Po-Chieh was our first visiting scientist. We have submitted an article to the *Journal of Electronic Imaging* based on Toru Tanaka's research on the color appearance of overhead-transparency projected images.

The size of our community has grown. The number of part-time students from local industry continues to increase. Similar to our industrial visiting scientists, part-time students contribute significantly to our total understanding of color science. Many of these scientists have significant expertise in non-color areas. As their knowledge of color increases, they perceive new opportunities to combine color and their scientific area of expertise. Our classes in color indicate a growing interest in color imaging. My introductory colorimetry graduate course had an enrollment of over twenty students.

The breadth of research has also increased. Color appearance forms a large component of our total research program. Faculty, full- and part-time students, and visiting scientists are actively involved in testing color appearance models. For the first time, we are also collecting visual data of corresponding colors. These data will enable us to derive models in addition to their testing. In the past, we have limited printer colorimetric characterizations to continuous-tone printers. This year we studied the color formation properties of desktop and large-format ink-jet printers. We have begun work with digital cameras; this research includes improved color correction algorithms for images with poor color accuracy due to limitations in automatic color balance and quantifying noise in color signal transformations. Color tolerance research has also returned to MCSL via our Industrial Color Difference Evaluation Consortium; this year we have begun a large visual experiment focusing on the perceptual dimension of hue.

On a personal note, this year seemed to pass very quickly. During our summer (unfortunately their winter), I was invited to Australia to participate in the Color Continuum Conference sponsored by Colorways Australia and the Australian Colour Society and lecture at the Royal Melbourne Institute of Technology. It was great to return to Australia, the last visit occurring during 1991 where I attended AIC and CIE conferences. I particularly enjoyed renewing my friendships with Barbara Marshall, Peter McGinnley, Paul Green Armitage, and Bryan Powell.

During the fall, I participated in the AIC interim meeting on color measurement. It was an excellent blend of science and application and I had a number of very useful discussions about the practical realities of setting industrial tolerances. These discussions influenced an article I wrote for *Color, Research, and Application* on the same topic. It was my first visit to Berlin. Walking through the city and seeing bullet holes in buildings, especially in residential areas, gave me a new perspective about the insanity of war.

Following the AIC meeting, I went to London to visit The National Gallery. They have an active research group in the color imaging of paintings. I was interested is seeing their multi-channel camera, color image processing software, and discussing research in spectral estimation, "removing" aged varnish computationally using Kubelka-Munk theory, and color reproduction using multiple inks to minimize metamerism between the original painting and its printed reproduction.

Before the spring, I thought I knew all there was to know about CRT colorimetry. I was wrong. I found out about the importance of accounting for inter-reflection flare in a colorimetric characterization of a Macintosh system used in our research. Interestingly, Kazuhiko Takemura noticed the identical problem when characterizing a Silicon Graphics system. A year earlier, Peter Bodrogi working with Janos Schanda told me about a similar experience. As a consequence, I have modified the MCSL model used for CRT colorimetric characterization and the CIE technical report that is nearing completion.

As always, MCSL achievements are results of group effort. I believe we have had a productive year. Our students, faculty, and staff have worked very hard. Our supporters have been generous and patient - a special note of thanks to Elizabeth Hunter, Eastman Kodak, and Hewlett Packard. Six students left us to begin their careers in color: Rick Alfvin, Chris Hauf, Audrey Lester, Jim Shyu, Hae Kyung Shin, and Seth Ansell. I wish them success!

FACULTY & STAFF ACTIVITIES

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

1995 proved to be another interesting and exciting time in the Munsell lab. As usual, I saw several students come an go. Rick Alfvin completed his thesis on observer metamerism in the spring and moved on to full-time employment with Eastman Kodak. Chris Hauf also wrapped up his years as a full-time RIT student and accepted a position with Kodak. His thesis on the development of color-appearance and color-reproduction software modules will be completed very soon. Sue Farnand, one of my part-time students, defended her M.S. thesis on the importance of image content on color discrimination and is now continuing her work at Kodak. I wish Rick, Chris, and Sue the best of luck in their future endeavors. Several part-time students (Cathy Daniels, Fritz Ebner, and Jack Rahill) continued working with me on their research while Karen Braun continued as a full-time Ph.D. student. Gus Braun joined me as a Ph.D. student and Alex Vaysman signed on as a part-time M.S. student. Gus will be doing research on color gamut mapping and Alex is examining the trade-offs between spatial and color resolution in color printing. I also have two undergraduates, Garrett Johnson and Meredith Graham, doing their senior research projects with me. I am very pleased to see my students doing well after they leave RIT and I appreciate all of the support they provide both during and after their time in the lab.

1995 also brought some exciting recognition of our research from our peers. Karen Braun's presentation of her work on the evaluation of color-appearance models in color reproduction was voted the best poster at the 1995 IS&T/SID Color Imaging Conference. Karen's dissertation on this topic will be completed in the first few months of 1996. After that she will be moving on to begin a new career with Xerox. Karen's award, combined with my acceptance of the 1995 C. James Bartleson Award in Williamsburg last February, made 1995 a very happy year for us.

One of the hardest questions I'm often asked is "what are you up to these days?" Usually I give the unsatisfying answer, "the same as usual." The real reason for this is that I'm usually doing several different things at the same time and I know that nobody really wants to hear about all of them. So I guess an annual report is the appropriate place to try to summarize what I'm up to. Usually I say that my research generally falls under the umbrella of cross-media color reproduction. Under this umbrella, I have been concentrating more on three areas lately: appearance modeling, gamut mapping, and observer metamerism. My appearance research has concentrated on the refinement and testing of models along with the interesting work of CIE TC1-34. Gamut mapping (dealing with the reality that different devices produce different ranges of colors) is an area that needs to be addressed once you're satisfied with the appearance modeling. Observer metamerism sets an as yet not-well-quantified fundamental limit to how hard we need to work to achieve the intrinsically metameric matches in color reproduction. Those are the topics that I'm working on these days with the help of all of the MCSL students and staff. Details of the ongoing research can be found elsewhere in this report.

I've also managed to set aside some time to work on some computer graphics. I've been using our SGI systems to render colorimetrically accurate 3D representations of various color spaces such as CIELAB, CIELAB L*C*h, Munsell, and OSA. This has been both fascinating and educational. It is an interesting experience to be able to "fly through" a 3D representation of the OSA UCS. These tools are also useful in our gamut mapping research. I hope to be able to share some of these visual experiences at some point in the future. I expect computer graphics will become an area of research at MCSL in the coming years.

On the teaching front, I am continuing to teach my "Vision and Psychophysics" and my "Color Appearance" graduate courses. The color appearance course has been transformed into a 2-day short course that was offered for this first time last summer and will be repeated in 1996. I will also be turning that material into a book for professionals needing to understand and address color appearance modeling issues. This winter I have been developing two new courses to be offered next year. One is a general overview of color reproduction at a more theoretical level and the second is a color systems course on the current state of technology.

Last year, I mentioned that Lisa and I added a baby Bernese Mountain Dog to our family. Our experience with Sierra has been so rewarding that we decided to move up the evolutionary ladder and we are excitedly expecting our first child in late February, 1996. This happy event will probably curtail my traveling a bit in the coming year, but that's OK.

Once again, thank you to all the students, faculty, staff, and supporters of the lab. I feel very fortunate.

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

This year has been a very full one. I became involved in the Industrial Color Difference Evaluation Consortium, directing the research of one of our M.S. students, Yue Qiao. The goal of this research is to increase the visual experimental data to advance the development of color difference equations. I have been very happy with the quality and progress of this project. Another major responsibility involved teaching Optical Radiation Measurements Laboratory, a two credit hour graduate instrumentation laboratory in the fall. The students stimulated great interest and kept me very busy. During the winter of this year we decided to end the 45/0 visible reflectance factor calibration service that I have been responsible for since starting work. This decision, although difficult, was best for the laboratory at the present time. The calibration service needed an investment of more time and money than fit the research interests of the laboratory and the personnel. Of course my responsibilities continue to include the care and feeding of our many instruments and personal computers and helping anyone who needs it. This year ended with a great personal accomplishment, the birth of my daughter, Acadia Reniff Fairchild. During the following academic year I will be working on a part-time basis in order to spend more time caring for her.

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

1995 has been an eventful one since I worked the majority of it pregnant and, in November, I was blessed with my new baby boy, Michael. Up until then, I performed my regular duties: the short courses of 1995 went well, we had a new visiting scientist arrive from Sony Corporation and the ChromaZone Newsletter is still informing. This coming year will prove to be quite a challenge prioritizing my responsibilities to fit into my new part-time schedule.

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

As a postdoctoral fellow in the lab, my main focus has been a research project involving color gamut mapping funded under the auspices of the NSF-NYS/IUCRC and NYSSTF-CAT Center for Electronic Imaging Systems. During the last year I completed the first part of this research in which I compared the efficacy of various gamut mapping techniques using simple rendered images and artificial gamut boundaries. The results were very encouraging and I presented them in February at the IS&T/SPIE Symposium on Electronic Imaging in San Jose, CA. The next immediate step is the preparation of a paper for publication in a forthcoming special issue of IEEE Transactions on Image Processing

The results from this work indicated that it may be possible to automate gamut mapping to some extent since certain algorithms were generally preferred across color for mapping chroma and lightness. An interesting aspect of the results was that the choice of independent color space may play a large role in the selection of mapping algorithms. This has sparked my interest in learning more about color appearance and uniform color spaces.

The next step in this research project involves incorporating gamut mapping in two dimensions at a time with more complex images and gamut boundaries. I expect that these experiments will take less time to implement and execute due the experience I've gained during the first phase and the ability to build on the computer tools I've already developed.

The lab has provided many opportunities for me to learn more about color science and bridge the gap between my knowledge of vision research and color science. Last summer, I sat in on Mark's and Roy's Industrial Color Seminars and I found them to be invaluable. I had the opportunity to serve on Susan Farnand's Masters Thesis committee. Again in the fall I sat in on the Color Science Seminar. I have also learned a great deal at our weekly lab meetings, and via discussions with the faculty and students and through participation in others' experiments. I look forward to participating with the lab during the final part of my fellowship and I would like to thank everyone in the lab for participating in my experiments and providing an active atmosphere that has been beneficial in more than just an intellectual way.

Koichi Iino, Visiting Scientist, Toppan Printing Co., Ltd.

I would like to thank Professor Roy Berns and other MCSL staff for helping me. I have acquired much knowledge in color science from classes and experience in MCSL this year. Professor Berns and I are writing an article which relates to an analytical characterization model for an Ink-jet printer. I hope it is going to be published in the near future.

Also, I continue my research and I believe it is progressing step by step.

Tsuneo Kusunoki, Visiting Scientist, Sony Corporation

It has been almost four months since I came to Rochester at the end of August. I saw beautiful nature scenes around Rochester this fall and now I am experiencing Rochester's winter. I have spent the last four months studying English at English Language Institute and auditing color science classes. They were very useful and have impressed me. I also started my first experiment in November 1995, studying the stability of a CRT over time. I appreciate the kindness of the faculty, the staff, and my colleagues.

In Japan, I am in charge of developing CRTs. Although a CRT is supposed to be a mature device, I believe that there is still room for improvement by considering human vision and devices in the imaging chain, such as printers, scanners, and cameras.

I hope to learn these things and utilize them in my research and in my job.

Kazuhiko Takemura, Visiting Scientist, Fuji Photo

About one and half years have passed since I came here and I am now experiencing my second winter in Rochester. I have learned a lot about American life and I am enjoying it too. It was a great surprise when I learned of the significant difference that exist among the colors of crayons between the United States and Japan.

Last year, I spent most of my time developing a comprehensive survey of past studies on color appearance and preparing some psychological experiments. However, this was really helpful in deepening my knowledge about the subject. I am now conducting a series of experiments and I hope my project will shape up nicely.

I would like to express my appreciation of all the kindness that the staff, faculty, colleagues, and my friends have done for me. Definitely, the Munsell Lab is an exciting and attractive place!

FULL TIME GRADUATE STUDENTS

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

Gus Braun, Ph.D., Candidate, Imaging Science
B.S., Imaging Science, Rochester Institute of Technology, 1989.
M.S., Imaging Science, Rochester Institute of Technology, 1991.
Thesis Topic: TBD

Karen Braun, Ph.D. Candidate, Imaging Science
B.S., Physics, Canisus 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

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

Tuo Wu, M.S. Candidate, Color Science
B.S., Mechanical Engineering, Beijing Printing Institute, 1984.
M.S., Printing, Rochester Institute of Technology, 1991.
Thesis Topic: T.B.D.

Animesh Bose, M.S. Candidate, Color Science
B.S., Printing, Regional Institute of Printing, India, 1985.
Thesis Topic: T.B.D.

PART TIME GRADUATE STUDENTS

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

Scott Bennett, M.S. Candidate, Color Science
B.S., Computational Mathematics, Rochester Institute of Technology, 1995.
Thesis Topic: TBD

Robert Poetker, M.S. Candidate, Color Science
B.S., Computer Engineering, University of Evansville, 1983.
Project Topic: Building Printer Device Profiles Using MATLAB

Peter Burns, Ph.D. Candidate, Imaging Science
B.S., Electrical & Computer Engineering, Clarkson, 1974.
M.S., Electrical & Computer Engineering, Clarkson, 1977.
Thesis Topic: Image Noise in Multispectral Color Imaging

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 and Slide Color Reproduction

Fritz Ebner, Ph.D. Candidate, Imaging Science
B.S., Electrical Engineering, Carnegie Mellon, 1986.
M.S., Electrical Engineering, University of Rochester, 1990.
Thesis Topic: Gamut Mapping Derived from Observer Matches in Simple Graphics and the Influence of Context on Gamut Mappings

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

Brian Hawkins, M.S. Candidate, Color Science
B.S., Electrical Engineering, Clarkson University, 1988.
Project Topic: Redetermination of the Color Gamut of Surface Colors

Greg Howell, M.S. Candidate, Color Science
B.S., Electrical Engineering, Ohio University, 1985.
Project Topic: Predicting Colorant Concentrations Using a Digital Camera

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

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

Dave Wyble, M.S. Candidate, Color Science
B.S., Computer Science, SUNY Brockport, 1992.
Thesis Topic: Colorimetric Contrast Sensitivity Functions

RESEARCH

Appearance Modeling and Psychophysics

The RLAB color-appearance space continues to generate significant interest and perform quite well in various model tests. The finishing touches were put on a paper detailing the latest refinements of the model. The results are a more complete model that has been mathematically simplified without negatively impacting its performance. This paper has been accepted for publication and will appear in *Color Research and Application* during 1996.

The surround in which an image is viewed has a significant impact on the apparent contrast of images. This topic was studied by Bartleson and was the topic of Mark Fairchild's Bartleson Lecture presented in Williamsburg in February. The lecture was adapted into a paper, "Considering the Surround in Device-Independent Color Imaging," that was recently published in *Color Research and Application*. These effects also form the basis of an M.S. project being carried out by Cathy Daniels. Cathy is examining the magnitude of the surround effect for specific viewing conditions and looking more carefully at the influence the surround has on chromatic, as well as luminance, contrast.

Karen Braun completed the second main phase of her Ph.D. dissertation. This phase was an evaluation of several color-appearance models for a variety of viewing conditions used in CRT-to-print image reproduction. These results confirm that the RLAB, CIELAB, and Hunt models work quite well in these situations. The results were presented at the IS&T/SID 3rd Color Imaging Conference and will be the subject of a journal article to be submitted shortly. A paper on the first phase of this research by Braun, Fairchild, and Alessi was accepted for publication and will appear in 1996. The final phase of this project is currently underway. In this phase, observers are adjusting imaged to make color-appearance matches across changes in viewing conditions. This will produce results that allow both the testing of current models and the development of future models. This experiment is expected to lay the groundwork for future color-appearance research at MCSL.

Mark Fairchild completed a series of appearance-model tests as part of the activities of CIE TC1-34. This work was summarized in a draft report that was circulated to the committee. The committee is currently considering how to proceed. The preliminary results indicate that RLAB performs very well as a simple model and that the Hunt model performs well in more complex situations. However, there are still revisions being made to some of the other models and new models being published so this area remains very active and is not likely to settle down for some time.

Ethan Montag is stretching our color-appearance psychophysics to problems of gamut mapping that deal with how to best reproduce a color when the desired color cannot be physically produced. This work is taking a more fundamental approach toward finding the best algorithms for modifying the colors in objects (rather than simple patches) while preserving the overall appearance of the object. The first results of this work will be presented at the SPIE/IS&T Electronic Imaging conference this winter. A journal article is being planned and a second phase of psychophysics is being developed.

Heui-Keun Choh and Roy Berns, last year, 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. An article describing the experiment was published in the *Journal of Electronic Imaging*.

Kazuhiko Takemura is conducting visual experiments to determine corresponding colors between Munsell samples illuminated with 6500 K filtered tungsten and a computer-controlled CRT display operated at two correlated color temperatures, 5000 K and 10,000 K. Observers are judging hue, lightness, and chroma. In addition to single stimuli, images will also be compared. The results of these experiments can be used to test existing appearance models and build a new color-appearance model.

Refereed Publications

M.D. Fairchild, "Refinement of the RLAB Color Space," *Color Res. Appl.,* **21** in press (1996).

M.D. Fairchild, "Considering the Surround in Device-Independent Color Imaging," *Color Res. Appl.,* **20** 352-363 (1995).

K.M. Braun, **M.D. Fairchild**, and P.J. Alessi, "Viewing Environments for Cross-Media Image Comparisons," *Color Res. Appl.,* **21** in press (1996).

M.D. Fairchild, "Testing Colour-Appearance Models: Guidelines for Coordinated Research," *Color Res. Appl.,* **20** 262-267 (1995).

M.D. Fairchild, "Testing Colour-Appearance Models: Guidelines for Coordinated Research," *CIE Publication* ***118/5*** , 39-46 (1995).

R.S. Berns and **H.K Choh**, "Cathode-Ray-Tube to Reflection-Print Matching Under Mixed Chromatic Adaptation using RLAB," *J. Electronic Imaging* **4**, 347-359 (1995).

Proceedings and Presentations

K.M. Braun, and **M.D. Fairchild**, "Evaluation of Five Color-Appearance Transforms Across Changes in Viewing Conditions and Media," *IS&T/SID 3rd Color Imaging Conference,* Scottsdale, 93-96(1995).

M.D. Fairchild, "Considering the Surround in Device-Independent Color Imaging, " 1995 C. James Bartleson Lecture, *ISCC Pan-Chromatic Conference,* Williamsburg (1995).

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

Mark Fairchild and Lisa Reniff's work on the time course of chromatic adaptation made it into print in the *Journal of the Optical Society of America A* during 1995. This work has served as a basis for much of our color-appearance psychophysics by allowing us to define viewing conditions with confidence that the observers are fully adapted to the appropriate stimuli. Currently, an exploratory project is underway to examine the possibility of using a stereoscopic computer graphics display system to perform haploscopic chromatic adaptation experiments.

Rick Alfvin presented the results of his M.S. thesis on observer metamerism at the Panchromatic Conference in Williamsburg and Mark Fairchild gave a related presentation at the Color Imaging Conference. This work examined observer variability in metameric color matching of simple split-field stimuli generated using color reproduction media. The results not only provide a useful estimate of observer variability, but they provide a fundamental limit on how good cross-media color matches need to be in order to please most of the people most of the time. The results were also used to evaluate CIE techniques for predicting observer variability. The CIE and other related techniques significantly under predict the magnitude of the experimental results. Thus, there is a need for a more accurate model. A computer simulation of human color matching functions is being carried out with the aim of providing a more accurate estimate of the spectral variability in color matching functions that could be used to generate more accurate estimates of the experimental results. A paper on the experiment has been submitted for publication and is currently in the review process.

Elizabeth Pirrotta (currently with Hewlett-Packard in Barcelona) made the trip to India to present the results of her M.S. thesis on the evaluation of chromatic adaptation models for simple, object-color stimuli. This work was completed a couple of years ago and led to some of the refinements of the RLAB model discussed above.

Po-Chieh Hung, while a visiting scientist with MCSL several years ago, and Roy Berns performed a visual experiment to determine lines of constant perceived hue using a colorimetrically-characterized CRT display. Their results were published in *Color Research and Application*. CIELAB, CIELUV, Hunt, and Nayatani color appearance spaces were evaluated to determine whether these hue loci plotted as straight lines. They concluded that none of these spaces have sufficient hue linearity. Ethan Montag has been plotting their visual results in cone excitation spaces and has found markedly improved correlation.

Peter Burns' Ph.D. dissertation research is concerned with image noise in multispectral imaging. The first phase of this research is to perform a multivariate error propagation for typical colorimetric systems such as spectrophotometers and three-channel colorimeters and cameras where the error is described using CIE94-corrected ellipsoids. Peter and Roy Berns have submitted an article describing this analysis. This analysis made use of a rotation between ΔL^*, Δa^*, Δb^* and ΔL^*, ΔC^*ab, and ΔH^*ab. Peter has submitted an article to *Color Research and Application* describing the errors associated with performing this rotation.

Roy Berns chairs a CIE technical committee whose goal is to evaluate whether rod intrusion has a significant affect on disrupting metameric matches. The analysis is computational and will evaluate typical metamers viewed under typical light booths. The committee is at the stage of defining a method to calculate the magnitude of rod intrusion.

Refereed Publications

M.D. Fairchild and **L. Reniff**, "Time-Course of Chromatic Adaptation for Color-Appearance Judgements," *J. Opt. Soc. Am. A*, **12,** 824-833 (1995).

P.C. Hung and **R.S. Berns,** "Determination of Constant Hue Loci for a CRT Gamut and their Predictions using Color Appearance Spaces," *Color Res. Appl.,* **20**, 285-295 (1995).

Proceedings and Presentations

M.D. Fairchild, and **R.L. Alfvin,** "Precision of Color Matches and Accuracy of Color Matching Functions in Cross-Media Color Reproduction," *IS&T/SID 3rd Color Imaging Conference***,** Scottsdale, 18-21 (1995).

E. Pirrotta and **M.D. Fairchild**, "Directly Testing Chromatic-Adaptation Models using Object Colors," *Proceedings of the 23rd Session of the CIE* (New Delhi) Vol. **1**, 77-78 (1995).

R.L. Alfvin and **M.D. Fairchild**, "Observer Metamerism: Precision of Color Matches and Accuracy of Color Matching Functions," *ISCC Pan-Chromatic Conference* (1995).

R.S. Berns, "Rochester Institute of Technology Promotes Color Science," *Digital Output*, Vol.**1**, No. 2, 40 (1995).

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 Voting Delegate to ISCC, Mark D. Fairchild.

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

ISCC Board of Directors, Mark D. Fairchild.

RESEARCH

Measurement, Formulation, and Tolerances

Yue Qiao and Lisa Reniff performed visual experiments scaling color tolerances, similar to MCSL research performed several years ago. This research is supported by the Industrial Color Difference Evaluation Consortium. The experiments are designed to extend the RIT-Dupont visual data base of color differences. In particular, they are measuring tolerances with hue error. The goal is to determine whether color difference equations should have corrections that depend on hue angle.

Roy Berns has written an article for *Color Research and Application* describing methods of setting industrial tolerances using pass-fail and colorimetric data. Optimizing the commercial factor by minimizing the number of instrumental wrong decisions, optimizing the l:c ratio, and deriving tolerance ellipsoids using logistic multiple-linear regression are described. This research was also supported by the Industrial Color Difference Evaluation Consortium. A portion of this research was presented at the AIC Interim Meeting held in Berlin during the fall.

Roy Berns has collaborated with David Alman from Dupont and Professors Melgosa, Hita and Poza from the Universidad de Granada (Spain) on defining the RIT-Dupont data set in the traditional ellipsoidal manner. The RIT-Dupont data were published as a set of vectors, each with constant visual difference. CIELAB and x,y,10Y ellipsoids were derived which will enable an easy comparison to previously published data bases. An article has been submitted to *Color Research and Application*.

Lisa Reniff, several years ago, described a method of diagnosing the spectrophotometric errors based on the colorimetric analysis of the cyan BCRA Series II tile. Reference black, reference white, and wavelength errors were considered. Roy Berns and Lisa have analyzed this method in more detail and calculated the effects of these errors on the accuracy of the entire tile set. An article has been submitted for publication in *Color Research and Application* detailing their analyses. These data will also be included in a CIE technical report on methods of characterizing spectrophotometers.

In many of our visual experiments, CRT displays are used as stimulus generators. This year Roy Berns has analyzed the importance of accounting for inter-reflection errors when characterizing the colorimetry of CRT displays. Depending on the faceplate properties such as the transmittance characteristics and refractive index of the glass and optical coatings, inter-reflection optical flare can have a large affect on the colorimetry of the display for dark colors. Methods have been developed to quantify this flare and the MCSL CRT equations have been modified to explicitly define inter-reflection flare. An article describing this research is in press in *Displays*. The modified equations will also be included in the CIE technical report on CRT colorimetry.

Colorant formulation is performed mainly in comparison to a material standard with known reflectance. However in some applications, a formulation is desired that is a trichromatic rather than spectral match. The formulation must only have particular CIELAB values for one observer-illuminant combination. Even so, it would be desirable that the selected formulation retain its color appearance upon changes in illumination. In other words, the best formulation is one that corresponds to a color-constant sample. Roy Berns has begun collaborating with Professor Boris Sluban of the University of Baribor (Slovenia) on formulation algorithms that optimize color constancy.

Refereed Publications

R.S. Berns, "Deriving Instrumental Tolerances from Pass-Fail and Colorimetric Data," *Color Res. Appl.,* in press (1996).

R.S. Berns, "Methods for characterizing CRT displays," *Displays*, in press (1996).

Proceedings and Presentations

R.S. Berns, "Applied Colorimetry Part I: Materials," *Optics Photonics News*, September, 23-27 and 53 (1995).

R.S. Berns, "CRT Colorimetry," oral presentation at Interest Group I meeting, *ISCC annual meeting*, April, Greensboro, North Carolina.

R.S. Berns, "To Optimize Or Not To Optimize (l:c) Ratios," *AIC Interim Meeting*, Berlin, September.

R.S. Berns, "Advances in Color Measurement," *Colour Continuum Conference*, Melbourne, August.

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.

Jim Shyu and Roy Berns have developed a software method to perform the spectral estimation of photographic images using a drum scanner. From an *a priori* analysis of a material's dye absorptivities, scanner data are used to estimate dye concentration. Using Beer-Bouguer or Kubelka-Munk theories, the spectra are estimated and colorimetric values calculated. A paper describing the research was published in the *Journal of Electronic Imaging*.

The accurate reproduction of CRT images as projected slides is desirable in many applications including the entertainment industry and data visualization. This area of research has been the subject of two master's theses (Audrey Lester and Hae-Kyung Shin). One needs to derive the relationship between digital data and spectral transmittance of the image recorder, the colorimetry of the CRT and projected slides, and the color appearance of both devices. An article describing this research was published in the *Journal of Electronic Imaging*.

Image compression is a common tool to reduce computer memory requirements. Any color space can be used to perform the compression. Nathan Moroney and Mark Fairchild performed a visual experiment in order define optimal color spaces for image compression using the JPEG algorithm. Their results were published in the *Journal of Electronic Imaging*.

An important aspect when defining the appearance of an image is the viewing surround. Surround relative luminance can have a dramatic effect on changing the perceived tone and color reproduction of an image. Mark Fairchild presented the Bartleson Lecture on this subject and published an article in *Color Research and Application*.

In the past, our research in printer device colorimetric characterization has been limited to continuous-tone devices. This year we have begun studying the color formation properties of ink-jet printers. Koichi Iino and Roy Berns evaluated the cluster-dot halftoning algorithm of an Apple Stylewriter ink-jet printer. A spectral-based model was used to define the color formation of this printer. A summary was published in the *Electronic Imaging* newsletter. A full article is in preparation. Animesh Bose and Roy Berns have begun evaluating the color formation properties of a Hewlett Packard large format ink-jet printer. In their research, they are evaluating the blue-noise (scatter mode) halftoning algorithm.

Refereed Publications

M.D. Fairchild, **R.S. Berns**, and **A.A. Lester**, "Accurate Color Reproduction of CRT-Displayed Images as Projected 35mm Slides," *J. Electronic Imaging*, **5** 87-96 (1996).

M.D. Fairchild, "Considering the Surround in Device-Independent Color Imaging," *Color Res. Appl.,* **20** 352-363(1995).

N. Moroney, and **M.D. Fairchild**, "Color Space Selection for JPEG Image Compression," *J. Electronic Imaging*, **4** 373-381(1995).

R.S. Berns and **M.J. Shyu**, "Colorimetric Characterization of a Desktop Drum Scanner using a Spectral Model," *J. Electronic Imaging* **4**, 360-372 (1995).

Proceedings and Presentations

K.M. Braun, and **M.D. Fairchild**, "Evaluation of Five Color-Appearance Transforms Across Changes in Viewing Conditions and Media," *IS&T/SID 3rd Color Imaging Conference,* Scottsdale, 93-96 (1995).

M.D. Fairchild, "Considering the Surround in Device-Independent Color Imaging," 1995 C. James Bartleson Lecture, *ISCC Pan-Chromatic Conference,* Williamsburg (1995).

R.S. Berns and **K. Iino**, "Spectral Modeling of an Ink jet Printer," *Electronic Imaging*, **5** No. 2, 3 (1995).

R.S. Berns, "Applied Colorimetry Part II: Imaging," *Optics Photonics News,* October, 23-27 (1995).

R.S. Berns, "Research in Device-Independent and Multi-Spectral Graphic Reproduction," *Colour Continuum Conference*, Melbourne, August.

R.S. Berns, "Color Imaging," *Royal Melbourne Institute of Technology*, August.

R.S. Berns, "Research in Colorimetric and Multi-Spectral Graphic Reproduction," *Milliken Research*, Greenville, South Carolina, September.

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.

IS&T/SID 1995 Color Imaging Conference, Mark D. Fairchild, Technical Committee Member.

FUNDING

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Endowed Scholarships

Franc Grum Memorial Scholarship

Macbeth-Engel Fellowship in Color Science

Visiting Scientists

Fuji Photo Film Ltd.	Sony Corporation
Toppan Printing	Samsung Aerospace Industries, Ltd.

Unrestricted Research Scholarships, Grants, and Gifts

Elizabeth Hunter.....$10,000

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

Hewlett Packard Company $46,000

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 and gamut mapping.

Industrial Color Difference Consortium (1995-1997)
Approximately $60,000 per year for research aimed at improving the correlation between colorimetric based tolerance equations and visual evaluations of perceived color difference.

EQUIPMENT DONATIONS

Donor	*Item Description*	*Value*
Colorcurve Systems, Inc.	Colorcurve Student Education Sets	$230
Hewlett Packard Company	HP DesignJet 650 and Supplies	$14,668
Rolf Kuehni	Classic Color Science Textbooks	$920
Tailored Lighting	Color View Splice Hardware	$2500
Joy Luke Turner	2 Munsell Student Color Sets	$70

COLOR SCIENCE M.S. CURRICULUM

Enrollment in the Color Science M.S. program during 1995 was 5 full-time and 11 part-time students.

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

June 5-7, 1995 **Principles of Industrial Color Measurement**
- Instructors: Drs. Roy Berns and Mark Fairchild
- 41 participants
- Some companies included: Hewlett Packard, Monsanto, Xerox, DuPont, Bayer Corporation, Anheuser-Busch, Inc. and Dow Chemical.

June 8, 1995 **Industrial Instrumental Color Matching**
- Instructors: Mr. Ralph Stanziola
- 33 participants
- Some companies included: Hewlett Packard, Monsanto, Xerox, DuPont, Bayer Corporation, Anheuser-Busch, Inc. and Dow Chemical.

June 12-14, 1995 **Device-Independent Color Imaging**
- Instructor: Dr. Roy Berns
- 24 participants
- Some companies included: IBM, Eastman Kodak, Xerox, Nabisco, and Pantone.

June 15-16, 1995 **Color-Appearance Models: Theory & Practice**
- Instructor: Dr. Mark Fairchild
- 20 participants
- Some companies included: Eastman Kodak, Hewlett Packard, IBM, and Xerox.

1996 Scheduled Short Courses

June 3-5, 1996 **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 6, 1996 **Industrial Instrumental Color Matching**

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, current software demonstrations, and a problem-solving session. Instructed by Mr. Ralph A. Stanziola of Industrial Color Technology.

June 10-12, 1996 **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 13-14, 1996 Color-Appearance Models: Theory & Practice

A 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.

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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.

1994

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).

A. Lester and **M.D. Fairchild**, "Thermochromism of Ektachrome 100 Plus Professional Transparencies Upon Projection, "*J. Imaging Sci. Tech.*, **38** , 332-338 (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).

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

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).

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

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

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," *J. 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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