RICHARD S. HUNTER PROFESSORSHIP
AND
MUNSELL COLOR SCIENCE LABORATORY

ANNUAL REPORT 1985-1986

Richard S. Hunter Professorship and Munsell Color Science Laboratory Annual Report on Activity September, 1986

A new academic year has just begun; therefore, it seems appropriate to review the activity of the past year, and to give an account of the stewardship of the Munsell Color Science Laboratory in absence of a Richard S. Hunter Professor. This is the third Annual Report on the management of the Munsell Color Science Laboratory and its related activities.

Despite the tragic death on December 20, 1985 of our first Richard S. Hunter Professor in Color Science, Appearance and Technology, Dr. Franc Grum, the four objectives set forth by Dr. Grum when the laboratory was first established remain as follows:

1. To provide undergraduate and graduate programs in color science, appearance and technology;

2. To carry on research and development in the above named areas of color and appearance;

3. To establish a sound standardization program in areas where standards are either void or difficult to obtain from other sources;

4. To provide an essential ingredient for the success of the first three -- namely, liaison with industry.

Here in summary form, is a report on what has been accomplished on each of the above listed four objectives.

I. ACADEMIC PROGRAM

The Munsell Color Science Laboratory resides in the College of Graphic Arts and Photography within the School of Photographic Arts and Sciences. During the past year the Department of Color Science was established within the School of Photographic Arts and Sciences to provide an administrative framework for academic coursework. Both undergraduate and graduate coursework are taught by Munsell Color Science Laboratory faculty.

The undergraduate course PIMG 313 Introduction to Colorimetry is offered to sophomores in the newly formed Center for Imaging Science. This course uses the text Principles of Color Technology, 2nd Edition by Billmeyer and Saltzman. A follow-up course for juniors and seniors is in the planning stage which will cover applications of colorimetry to imaging science. The course

PPHT-313 Color Measurement is given to students in the Imaging and Photographic Technology Department within the School of Photographic Arts and Sciences. Topics include basic colorimetry and densitometry and this course also uses Billmeyer and Saltzman's text.

Beginning Fall quarter, 1986, the Munsell Color Science Laboratory through the Department of Color Science will be offering a Master of Science degree in Color Science, Appearance, and Technology. This is the first graduate program in color science awarding a degree by the same name. A description of the program from the R.I.T. graduate catalog is appended. This degree program will enable students with diverse backgrounds such as computer science, physics, textile chemistry, and graphic arts to study color science at an advanced level. Students in the Master of Science degree program in Imaging Science within the Center for Imaging Science will also be taking our courses as technical electives.

In order to compete with other institutions of higher education, we are aggressively seeking avenues for monetary support for incoming graduate students. At the time of this report, R.I.T.'s Graduate School has designated $9000 per academic year towards graduate support. This will cover tuition for one student. Through a New York State Center of Excellence grant, we can support one student with both tuition and stipend. A scholastic award in memory of Dr. Grum is being established.

The Laboratory was inaugurated in 1984; since then, several students from the Center for Imaging Science have concentrated in color science by taking our coursework and performing research in the Munsell Color Science Laboratory. The following is a listing of these students and their current employers:

Paul Butterfield, B.S. 1984, Eastman Kodak Co.
Christopher Pearson, B.S. 1985, Eiconix Corporation
Eric Walowit, B.S. 1986, Mead Imaging Corporation
Steven Bloomberg, B.S. 1986, Xerox Corporation
Michael Keating, B.S. 1986, Burlington Industries
Mark Fairchild, M.S. 1986, Munsell Color Science Laboratory
Mitchell Miller, M.S. expected 1987, Mead Imaging Corporation
Richard Riffel, M.S. expected 1988, Milton Roy Company
Jan Rosenbaum, M.S. expected 1988, Matrix Instruments

II. RESEARCH & DEVELOPMENT

A. Laboratory Development

During the last year, we have concentrated on organizing our facilities to best utilize limited space both for effective teaching and research. The main laboratory was divided into two sections in which one side is devoted to teaching activities, the other primarily standards and research activity. In this manner, instruments devoted to each activity are physically separated. There are also five small research rooms. The first is devoted to psychophysics. In this room, color vision tests, color order systems, and our new image processor are housed (this system is fully described in the following section). The second research room houses our radiometers. A Tracor Northern array radiometer and an Optronics Laboratories conventional spectroradiometer are situated on opposite ends of a 3 meter optical bench. The electronic hardware is isolated in the back of the room. The third research room houses the Munsell Color Science Laboratory goniospectrophotometer and other geometric instruments such as glossmeters and an abridged goniophotometer. The fourth room is used for storage and for making PTFE pressings to be used as standard reference materials. The final research room houses analytical spectrophotometers and a light booth used for color difference experiments. Each research room has two sections. The back section (about one quarter of the total area) is used as office space by our graduate students.

During the past academic year, the following equipment was received:

Applied Color System 1800 computer color matching system; a combination of an indefinite loan and purchase valued at $35,800.

Various Xenon flash sources used in reprography; a donation from the Eastman Kodak Company valued at $1,000.

Archival color order systems including early editions of the Color Harmony Manual donated by Mr. Walter G. Granville.

Macbeth Spectralight SPL75-B; a donation from Macbeth valued at $2,600.

Various colorimetric and photometric instruments used in psychophysical experiments by Mr. Edwin Breneman to study chromatic adaptation. This includes 2 high-intensity visual colorimeters and a Gamma Scientific telecolorimeter; An indefinite loan from the Eastman Kodak Company valued at $50,000.

Xerox 6065 personal computer including color monitor, a 10 megabyte hard disk and software; a donation by Xerox Corporation valued at $6,000.

Milton Roy Color Scan 45 spectrophotometer; an indefinite loan by Milton Roy APD valued at $10,000.

Dr. Grum's personal library of textbooks, CIE publications, and scientific reprints; a donation by the Grum Family valued at $1000.

A listing of the equipment as of March, 1986 is appended. The current estimated value of the laboratory is approaching $1,000,000.

B. Completed Research Activity

In our 1985 Annual Report, a large number of research activities were listed. Six of these have been completed and are summarized below.

1. Spectrophotometric Colorant Formulation Based on Two-Constant Kubelka-Munk Theory

A new approach to computer color formulation based on non-linear least-squares techniques has been developed to characterize colorants and predict their behavior in mixtures. This approach allows the optimization of absorption and scattering calculations to characterize these colorants. This same method has been used to directly match the spectral reflectance of a standard with a mixture of colorants that yields nearly the same spectral reflectance as the standard being matched. Several advantages have been gained over more traditional methods: Kubelka-Munk absorption and scattering coefficients have been determined without primary binary blends, the spectral reflectance of the standard and proposed formulation exhibit lower spectral difference, the use of spectrally similar colorants has been improved and, formulations can now be predicted for standards measured over wavelength regions other than the visible spectrum. This technique was particularly effective for the color matching of blended fibers.

From this research three articles are planned: the first on constructing the K & S database, the second on implementing the formulation algorithms, and the third the combination of the two methods into a single software package. The first article has been submitted to Color Research and Application authored by Eric N. Walowit, Cornelius J. McCarthy, and Roy S. Berns.

2. Illuminant Sensitivity of Artist Materials

An analysis was performed on artist materials used in paintings to determine their color appearance stability under lighting typically used in museums and gallery environments. This study used both Kubelka-Munk and chromatic adaptation theories. Several conclusions were drawn from this study. The first relates to the lighting conditions the majority of museums use, namely incandescent illumination. If we assume accurate color rendition is an important criterion in lamp selection, incandescent sources are not appropriate sources for illuminating paintings in which the artist's work environment was north-sky daylight. The second conclusion relates to the opinion of some artists and museologists that fluorescent lamp light is always a poor choice for illuminating art work. Our results indicated quite clearly that a properly selected fluorescent lamp such as deluxe cool white may be far superior to an incandescent lamp.

This work has been accepted for publication in Color Research and Application. It is titled "Exhibiting Art Work: Consider the Illuminating Source" by Roy S. Berns and Franc Grum.

3. Implementation of Recommended Ocular Exposure Thresholds For The Evaluation of Xenon Flashes

A system was established for the evaluation of sources of optical radiation with respect to recommended ocular exposure limits. This system consists of a diode array radiometer calibrated for absolute radiometric measurements and software for the application of the currently accepted threshold limits for exposure to various wavelengths of radiation. Absolute calibration of the array radiometer was accomplished to within 3 percent of values obtained with a conventional instrument. Day-to-day repeatability of the instrument indicates the possibility of absolute calibration of the detector array responsivity for everyday use in the measurement of continuous sources to an accuracy of plus-or-minus 2.8 percent. It was also determined that the output of several optical sources used in amateur photography can exceed the retinal thermal Threshold Limit Value. One typical 35 mm photographic flash exceeded the threshold at a range of 3 meters. Other threshold expressions were not exceded at significant distances or exposure durations for these sources.

An article based on the results of this study has been submitted to the Journal of Imaging Technology authored by Mark D. Fairchild and Roy S. Berns.

4. An Investigation of New Methods to Improve the Accuracy of Spectrophotometric Measurements

Spectrophotometers used in the Munsell Color Science Laboratory are carefully calibrated for photometric and wavelength accuracy. Deficiencies in instrument optics and electronics will always result in a small amount of residual error between measured data and absolute data as provided by standardizing laboratories such as the National Bureau of Standards. Therefore, it was of interest to develop mathematical algorithms to correct this residual error. Typically, this has been accomplished by the selection method in which each type of error is isolated and mathematically corrected. This method requires standard reference materials which isolate each type of error. Robertson, in a paper presented to CORM, described a matrix inversion method based on linear regression to correct spectral data. As a third method, we realized that principles of digital image processing could be applied to correcting this residual error. Software was written and these three methods were compared to determine which method was most robust in correcting spectrophotometric errors using BCRA tiles as transfer standards. Our results indicate that Robertson's method is the most effective method for correcting data. We plan to write articles based on these results in Color Research and Application and Applied Optics authored by Roy S. Berns and Kelvin Peterson.

5. Visual Determination of Color-Difference Ellipsoids Using Probit Analysis

It is well known that there is not a color difference equation which is perceptually uniform. We have completed a visual experiment to generate a new data base of color difference ellipsoids. These results will enable better color difference equation modeling and testing. The results of the study have been accepted for oral presentation at the 1987 CIE meetings in Venice, Italy. The submitted abstract is appended.

6. Goniospectrophotometric Characteristics of White Reflectance Standards With Respect to the CIE Normal/45 Geometry

At last year's A.I.C. conference in Monte Carlo, Dr. Grum reported on the use of the Munsell Color Science Laboratory goniospectrophotometer to evaluate white standard reference materials. Further research was performed to address the CIE recommended view-angle limits for normal/45 geometry. The results of this research have been accepted for oral presentation at the 1987 CIE meetings in Venice, Italy and for oral presentation at 1987 ISCC Williamsburg conference in color appearance. The submitted abstract is appended.

C. Current Research Activity

The Munsell Color Science Laboratory is concerned with the application of color in many diverse areas. The use of color in electronic imaging is emerging as a very important tool for communicating chromatic information. We are putting together an image processing system capable of displaying color on a CRT under spectroradiometric control. This equipment will be used in psychophysical research exploring color appearance questions such as chromatic adaptation and the transformation between softcopy color and hardcopy color. The following lists the major pieces of equipment comprising the image processor:

Xerox 6065 personal computer, Number Nine Revolution 512x32 bit single board graphics controller, Media Cybernetics Halovision Software, low cost RGB monitors, a studio-quality RGB monitor, and a spot spectroradiometer.

We are currently securing a spot spectroradiometer and researching studio-quality RGB monitors. The first phase of this research is to characterize, as completely as possible, the radiometric and colorimetric properties of CRTs, and their calibration for use as visual stimulus generators. The following parameters will be addressed: intergun relationships, the image microstructure of the dot field, the goniospectroradiometric properties of the face plate, and temporal and spatial stability. This research is being performed by Mr. Ricardo Motta, a graduate student in the Center for Imaging Science.

Recently, there has been some concern over the accuracy of spectral irradiance measurements of pulsed sources using array radiometers. This would include the measurement of both xenon flash sources and CRTs. A project has begun in which both an array radiometer and a conventional spectroradiometer will measure the spectral irradiance of a continuous incandescent source optically chopped to various frequencies including 30 Hz and 60 Hz as well as xenon flash sources and CRTs. This research is being performed by Mr. Wayne Farrell, a graduate student in the Center for Imaging Science.

Last year at the AIC conference in Monte Carlo, Monaco, Dr. Berns presented results of a statistical study on industrial illuminant metamerism. During the past year this research has been extended in two areas. The first is to reanalyze the reported results using more sophisticated statistical techniques including discriminant analysis and multivariate analysis of variance. This research is being performed by Dr. Berns and Mr. Fairchild. These analyses are based on colorimetric data calculated for daylight, incandescent light, and several fluorescent sources. We are also interested in statistically analyzing the reflectance spectra generated in this study. Mr.

Frank Zimmerman, an undergraduate student in the Center for Imaging Science, is analyzing these spectra using principal component analysis and Jozef Cohen's solution to Wyszecki's metameric black hypothesis. We hope to use these results to develop an index of metamerism based on spectral differences and provide a statistical data base for use in optimizing camera-taking sensitivities and other color reproduction applications.

Finally, the Munsell Color Science Laboratory was established to conduct research in color science, appearance, and technology. The first phase towards fulfilling this charge was to develop the physical facilities and obtain the necessary instrumentation. The tools are in place and the majority of the current and past research has been oriented toward metrology issues. We are keenly aware that color is a perceptual phenomenon; a program committed to the quantitative study of color must perform research in color perception. To meet this challenge we are developing a CRT stimulus generator as described above. We will also be building a visual colorimeter to be used to measure color matching functions and for color appearance studies; space has been dedicated in our main laboratory and monetary resources have been obtained. The colorimeter will be built by Mr. Mark Fairchild, a faculty member with the Munsell Color Science Laboratory. This instrument will include several components on loan from the Eastman Kodak Company. Professor W. D. Wright has gratiously offered his assistance in the design of the instrument.

III. STANDARDS ACTIVITY

The third major activity of the Laboratory is to provide standardized measurements and standard reference materials in areas where standards are either void or difficult to obtain from other sources. During this last year we have obtained a license from PPG Industries, Inc. to sell pressed PTFE (Halon) powder as a photometric standard. We have developed methodologies to scinter pressed Halon tablets to increase their durability. These are being provided both calibrated and uncalibrated.

An area of standardization which is becoming more and more important is the ability to measure the spectral reflectance of objects using geometries other than those specified by the CIE. For example, non-standard angles are required to characterize the optical properties of metallic automotive finishes. In order to improve inter-laboratory agreement when making these measurements, transfer standards are required. The current accepted practice is to assume materials such as pressed barium sulfate are Lambertian. Although it is well known barium sulfate is not Lambertian, there are few viable alternatives. A related problem is the accurate photometric calibration of diffuse reflectance measurements using integrating spheres in which a black trap is placed at the specular port. Differences in sphere diameter and specular port diameter make inter-laboratory comparisons impossible unless the goniospectrophotometric properties of the reference white are known. In order to address both of these industrial problems, we have begun research to develop a method for preparing a pressed powder such as PTFE for use as a primary transfer standard for goniospectrophotometry. This research will be performed by Mr. Denis Daoust, a graduate student in the Center for Imaging Science. We will be working closely with Dr. J. J. Hsia from the National Bureau of Standards. Dr. Hsia is also Chairman of the CIE TC 2-11 Committee on Gonioreflectometry of Standard Materials.

The Munsell Color Science Laboratory is participating in the following technical committees relating to standards activity:

ASTM E-12 Appearance of Displays
CIE TC1-07 Observer Metamerism
CIE TC2-03 LED Measurement Intercomparison
CIE TC1-10 Colorimetry of Self-luminous Displays
CIE TC2-11 Gonioreflectometry of Standard Materials
CORM-NBS Task Force for Intermediate Standard Laboratories
CORM-NBS Task Force for Array Radiometry

IV. INDUSTRIAL LIAISON

In order to insure that the full activities of the Munsell Color Science Laboratory are relevent to current scientific and industrial needs, the Munsell Color Science Laboratory Advisory Board was established. The Board has established the following charter:

"An advisory Board shall be established in conjunction with the Munsell Color Science Laboratory of the Rochester Institute of Technology. The function of the Board shall be to provide advice and recommendations relating to technical matters of concern to the planning and conduct of research and academic programs in the Laboratory.

The Director of the Munsell Color Science Laboratory shall appoint members to the Board as he deems appropriate. Members shall be chosen to provide a broad base of technical and industrial knowledge considered helpful to the purposes of the Board. They shall serve without pay and hold no formal status on the faculty or staff of the Rochester Institute of Technology by virtue of membership on the Board. The term shall be renewed annually.

The Director shall convene meetings of the Board, in whole or in part, as appropriate to consult with members of the Board on matters of technical planning and conduct of the research undertaken by the Laboratory.

The Director shall insure that members of the Board are apprised of the activities of the Laboratory periodically, but not less than once each year."

The Board is comprised of the following academic and industrial experts:

Dr. C. J. Bartleson, Chairman (Eastman Kodak Company), Dr. R. S. Berns, Secretary (Munsell Color Science Laboratory), Dr. P. K. Kaiser (York University), Dr. D. H. Alman (E. I. duPont deNemours Company) Dr. F. W. Billmeyer, Jr. (Consultant), Dr. L. J. Thomas (Eastman Kodak Company), Dr. K. D. Mielenz (National Bureau of Standards), Mr. J. Kaufman (Illuminating Engineering Society), Dr. J. Mukherjee (3 M), Mr. C. S. McCamy (Macbeth), Dr. V. S. Mihajlov (Xerox Corporation), Ms. J. T. Luke (Studio 231), Mr. R. S. Hunter (Hunter Associates), and Mr. R. Stanziola (Consultant).

The current members have served on the Board since March, 1985. They have provided input into the Master of Science degree, current and completed research projects, the technical content of our industrial short courses, and identifying candidates for the R. S. Hunter Professorship in Color Science, Appearance, and Technology.

V. DONATIONS

In addition to the aforementioned donations of equipment, the following monetary donations were received in support of the continued development of the Munsell Color Science Laboratory:

PPG Industries Foundation	$5,000
Eastman Kodak Company	$5,000
Xerox Corporation	$8,000
Richard and Elizabeth Hunter	$10,000
E. I. DuPont deNemours, Inc.	$10,000

A scholarship fund in the name of Dr. Franc Grum was established. Individual donations currently total approximately $1,500. The Inter-Society Color Council has donated $2,500 in memory of all the color scientists who have recently passed away.

VI. SYMPOSIA, SEMINARS, ORAL PRESENTATIONS, AND ARTICLES

<u>Advanced Concepts of Color and Color Measurement</u> was hosted by Dr. Grum, August 26-28, 1985. The course was presented as a succession of lectures on six major topics by leading scientific

experts. Approximately forty participants were in attendance.

The Matrix R Conference, a topical single-day event, was held May 9, 1986. The conference focused on reviewing recent significant developments by Dr. Jozef Cohen concerning his solutions to Wyszecki's metameric black hypothesis. Twenty leading scientists in the fields of colorimetry, vision, and lighting engineering were in attendance. This was the first conference of its type offered by the Munsell Color Science Laboratory. Costs were kept at a minimum and the topic was based on current research. Conferences of this type will become an annual event.

COLORIMETRY, An Intensive Short Course for Technicians and Marketing Personnel was given May 19-20, 1986. The course was designed to educate industrial personnel on the applications of colorimetry to quality control. Sixteen participants were in attendance.

COLORIMETRY, An Intensive Short Course for Scientists and Engineers was held June 2-4 and August 18-20, 1986. This course was designed to educate industrial personnel in the development of colorimetry and its practical application. Twenty participants attended each session.

Roy S. Berns, "The Use of Chromatic Adaptation Transforms in Color Reproduction", presented to the Rochester, New York Chapter of the Society of Photographic Scientists and Engineers, December, 1985.

Mark D. Fairchild and Franc Grum, "Thermochromism of Ceramic Reference Tiles," Applied Optics, 24, 3432-3433 (1985).

Roy S. Berns and Fred W. Billmeyer, Jr., "Development of the 1929 Munsell Book of Color, a historical review,"Color Research and Application, 10, 246-250 (1985).

Roy S. Berns, "A FORTRAN program for predicting the effects of chromatic adaptation on color appearance based on current CIE recommendations," Color Research and Application, 11, 82-88 (1986).

Roy S. Berns, "Aspects of metamerism and illuminant sensitivity of artists' paints," presented at the 1986 ISCC Williamsburg Conference.

Roy S. Berns and Franc Grum, "Illuminating Artwork: Consider the Illuminating Source", to be published in Color Research and Application, 1986.

VII. STAFF

The activities of the Munsell Color Science Laboratory and Department of Color Science are directed by the Richard S. Hunter Professor in Color Science, Appearance and Technology. The professorship is currently vacant and a search is underway. Dr. Roy S. Berns, Associate Professor, has been named the Interim Director of the Laboratory and Acting Chairman of the Department of Color Science until the Hunter Professorship is filled. He is assisted by Mr. Mark D. Fairchild, a recent graduate in the Master of Science program in Imaging Science, who was hired as an Instructor. Mr. Fairchild's responsibilities will include both teaching and research. Finally, Ms. Donna Shaw was recently hired as Laboratory Secretary.

VIII. CONCLUSION

This past academic year has been both a sad and exciting year. The absence of Dr. Franc Grum has created a void which will take many years to fill, if ever. I have been told that the effective performance of any job requires inspiration and perspiration. Franc's vision remains an inspiration. Perspiration will never be in short supply. With a graduate program in place, the Laboratory unusually well equipped, and internal and external support unwaivering, the Laboratory remains, as Dr. Grum often stated, "Nulli Secondus!"

IX. ACKNOWLEDGEMENTS

On behalf of the Munsell Color Science Laboratory, I would like to thank the many individuals and corporations whom have supported our activities generously . This support has been monetary, intellectual, and spiritual.

Roy S. Berns
Interim Director

APPENDICES

Reprinted from 1986 R.I.T. Graduate Catalog

Master of Science Degree in Color Science, Appearance, and Technology

Dr. Roy S. Berns, Coordinator
MS Program, (716) 475-2784
or (716) 475-6013

Color science is broadly interdisciplinary, encompassing physics, chemistry, physiology, and psychology. The curriculum leading to a master of science degree in color science, appearance, and technology is a program developed to educate students using a broad interdisciplinary approach. This is a unique opportunity for students as this is the only graduate program in the country devoted to this discipline. The program is designed for students whose undergraduate majors are in imaging science, photography, printing, textiles, physics, chemistry, psychology, physiology, graphic or fine arts, or any discipline pertaining to the quantitative description of color. Candidates who do not have adequate undergraduate work in related sciences must make up foundation courses before matriculating into the program.

The color science, appearance, and technology major provides graduate level study in both color science theory and its practical application. The program will give students a broad exposure to the field of color and will afford students the unique opportunity of specializing in a particular area appropriate for their background and interest. This objective will be accomplished through the program's core courses, selection of electives, and completion of the thesis.

The degree program in color science, appearance, and technology revolves around the activities of the Munsell Color Science Laboratory. The Munsell Laboratory is already the pre-eminent academic laboratory in the country devoted to color science. Since its inauguration in 1984, two industrial conferences have been held, both drawing participants from around the world. Industrial seminars devoted to the quantitative specification of color are offered on a continuing basis. Students have received co-op and full-time positions through contacts made with the assistance of the Munsell Laboratory.

The Program

The color science, appearance, and technology major is a full-time or part-time master's degree program. The length of time required to earn a degree varies according to the student's undergraduate preparation in mathematics, computer science, general science, and the number of courses taken per quarter. All students must earn 45 credits as a graduate student, 36 of which must be taken at RIT, to earn the master of science degree. For full-time students, the program requires a minimum of 4 quarters of study at the graduate level. Part-time students generally require 7 quarters of study at the graduate level. The curriculum is a combination of required courses in color science, appearance, and technology, elective courses appropriate for the candidate's background, and a research thesis. Candidates who wish to enter the program, but lack adequate preparation may have to take as many as 22 credits of foundation courses in mathematics, computer science, and general science prior to matriculation with graduate status. Foundation courses can be completed in two quarters.

The Foundation Program

The color science, appearance, and technology major is designed for the candidate with an undergraduate degree in a scientific or non-scientific discipline. Candidates with adequate undergraduate work in related sciences will start the program as a matricualated graduate student.

Candidates without adequate undergraduate work in related sciences must take foundation courses prior to matriculation into the graduate program. These students will enter the program as "Special Students." This will help identify the candidate in foundation courses, and allow for guidance from the director of the program.

Course work in mathematics, computer science, and general science is expected if these courses are not indicated on the candidate's transcript. Students who require foundation courses may be required to take as many as 22 credits in these subjects. A written agreement between the candidate and the director of the program will be developed to identify the courses required to complete the foundation course requirements.

Foundation courses must be completed before a student can matriculate into the graduate program, and the student must earn an overall B average in these undergraduate foundation courses to be accepted. A maximum of 9 credit hours at the graduate level may be taken prior to matriculation into the graduate program.

Foundation Courses

The courses listed below represent the courses required to meet the foundation course requirements:

SMAM 214, 215 Introduction to Calculus I, II—3 cr/qtr

SPSP 211, 212 College Physics I, II—3 cr/qtr

SPSP 271, 272 College Physics Lab I, II—1 cr/qtr

ICSP 220 FORTRAN Programming for Engineers—4 cr

GSSP 509 Psychology of Perception—4 cr

It should be noted that these foundation courses prepare the student only for required course work in color science, appearance, and technology. Additional undergraduate course work may be necessary in order to have the appropriate requirements for graduate electives offered in other areas.

Professor Berns aligning goniospectrophotometer to measure the color and surface attributes of a chromatic sample. The instrument was designed by the first Richard S. Hunter Professor, Dr. Franc Grum.

Program Requirements

The master of science degree program in color science, appearance, and technology requires the completion of 45 quarter credit hours of study including 9 hours for the thesis. If foundation courses are not required, the program can be completed in 4 quarters at full-time status and in 7 quarters at part-time status. Students who are qualified in one or more of the required courses may substitute other course work with the permission of the director of the program. The program curriculum is a combination of required courses in color science, appearance, and technology and elective courses which will satisfy the student's individual needs. The student may choose elective courses with the approval of the director of the program. This flexibility enables the program to be broadly interdisciplinary.

Required Graduate Courses

(PPHC 701) Colorimetry I—4 cr

(PPHC 702) Colorimetry II—4 cr

(PPHC 751) Special Topics: Color Perception—3 cr

(PPHC 801) Advanced Colorimetry—3 cr

(PPHC 802) Colorimetric Instrumentation and Standardization—4 cr

(PPHC 803) Computer Colorant Formulation—3 cr

(PPHC 890) Research Thesis—9 cr

(CQAS 711) Fundamentals of Statistics I—3 cr

(CQAS 712) Fundamentals of Statistics II—3 cr

Electives

Appropriate electives should be selected to bring total course work to 45 credit hours. The following is a partial list of possible recommended electives:

(CQAS 801, 802) Design of Experiments I, II—3 cr/qtr

(CQAS 821, 822) Theory of Statistics I, II—3 cr/qtr

(CQAS 830, 831) Multivariate Analysis I, II—3 cr/qtr

(PIMG 741, 742, 743) Analysis and Evaluation of Imaging Systems—3 cr/qtr

(PPRT 702) Graphic Reproduction Theory—4 cr

(PPRT 722) Ink, Color and Substrates—4 cr

(SCHO 736) Spectrometric Chemical Identification of Organic Compounds—3 cr

(SCHA 711) Instrumental Analysis—3 cr

(ICSA 770) Fundamentals of Computer Graphics—4 cr

(ICSA 771) Advanced Topics in Computer Graphics—4 cr

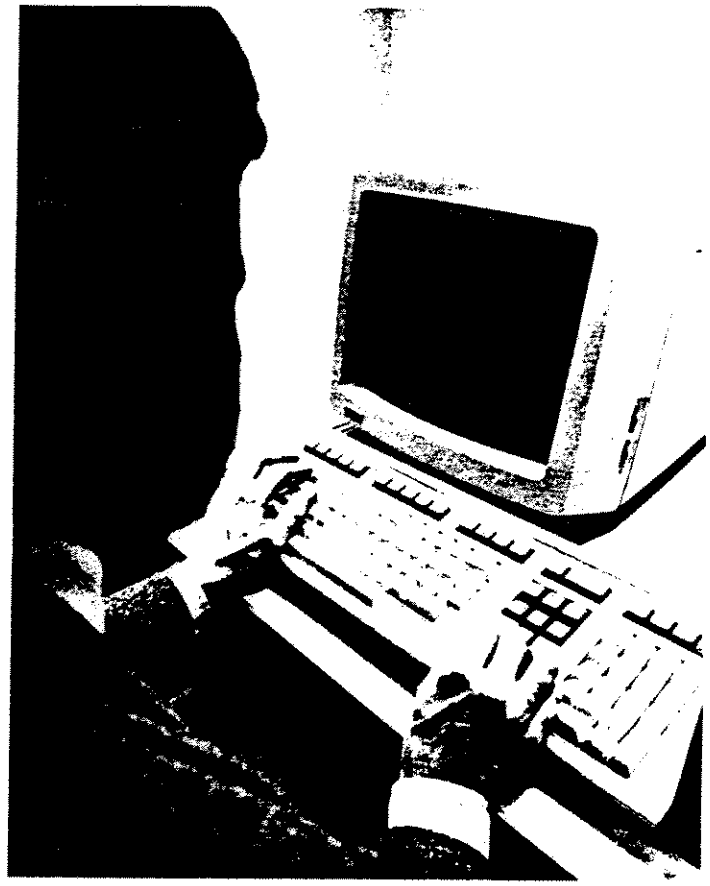
Thesis

Nine credit hours are required. Topics should be chosen that complement the candidate's undergraduate training. The technical advisory board to the Munsell Color Science Laboratory, in addition to the director of the program, can aid the candidate in selecting a thesis topic which has current industrial relevance.

Admission Requirements
Prior to being admitted to the master of science degree program, applicants must satisfy the director of the program in that their previous training, ability, practical experience, and education indicate a reasonable chance of success. Applicants may be admitted who hold a baccalaureate degree from an accredited institution. Applicants must have undergraduate records of 3.0 or higher. They will be required to take the Graduate Record Examination (GRE) as an aid in academic counseling during the development of the individual's program of studies.

Requirements are:
Graduate application
Earned baccalaureate degree
Graduate record examination (GRE)
Official undergraduate transcript
Two professional recommendations
An on-campus interview when possible
Undergraduate GPA of 3.0 or higher
Foundation course work 3.0 or higher, if required
TOEFL score of at least 550 (international students)

Munsell Advisory Board
In order to insure that the research activities surrounding the degree program are relevant to current industrial needs, the Munsell Color Science Laboratory Advisory Board was established. The board members have expertise in color vision, color measuring instrumentation, psychophysics, computer colorant formulation, lighting, art, and applied color technology. The Advisory Board provides an excellent resource for students in both the selection of a thesis topic and future placement.



A Typical Part-Time Schedule of Courses

	Credits
Fall	
PPHC 701 Colorimetry I	4
CQAS 711 Fundamentals of Statistics I	3
Winter	
PPHC 702 Colorimetry II	4
CQAS 712 Fundamentals of Statistics II	3
Spring	
PPHC 801 Advanced Colorimetry	3
Graduate Electives	4
Summer	
Graduate Electives	6
Fall	
PPHC 751 Color Perception	3
PPHC 802 Color Instrumentation and Standardization	4
Winter	
PPHC 890 Thesis	6
Spring	
PPHC 803 Computer Colorant Formulation	3
PPHC 890 Thesis	3
Total	46

A Typical Full-Time Schedule of Courses

	Credits
Fall	
PPHC 701 Colorimetry I	4
CQAS 711 Fundamentals of Statistics I	3
Graduate Electives	5
Winter	
PPHC 702 Colorimetry II	4
CQAS 712 Fundamentals of Statistics II	3
Graduate Electives	5
Spring	
PPHC 801 Advanced Colorimetry	3
PPHC 804 Computer Colorant Formulation	3
PPHC 890 Thesis	4
Graduate Electives	2
Fall	
PPHC 751 Color Perception	3
PPHC 802 Colorimetric Instrumentation and Standardization	4
PPHC 890 Thesis	5
Total	48

Color Science, Appearance and Technology

PPHC-701 **Colorimetry I**

Registration #0923-701
For those taking colorimetry for the first time. Covers colorimetric procedures commonly used in industrial quality control and research and development. The emphasis is on the spectral and colorimetric characterization of chromatic stimuli using modern instrumental methods, and deriving the relationships between appearance attributes and instrumental data. Accompanying laboratory stresses instrumental measurements.

Credit 4

PPHC-702 **Colorimetry II**

Registration #0923-702
(A continuation of Colorimetry I) The emphasis is on visual methods to determine color tolerances, characterizing surface properties of objects, visual scaling techniques using color order systems, and the effects of viewing and illuminat-
ing conditions on color appearance. Accompanying laboratory stresses visual measurements.

Credit 4

PPHC-751 **Special Topics: Color Perception**

Registration #0923-751
This course describes how we see color and what measurements of color mean. It includes information about the anatomy and physiology of the mechanism of vision and relates activities in that mechanism to the appearances of perceived colors. Methods for measuring and specifying color appearances are discussed. The implications and limitations of various kinds of color measurement are emphasized. Laboratory work includes measuring certain visual functions and using the data to make colorimetric specifications.

Credit 3

PPHC 801 **Advanced Colorimetry**

Registration #0923-801
A detailed treatment and evaluation of current research and development in color science. Topics include current developments in CIE technical committees, luminescent colorimetry, color rendering of light sources, observer metamerism, color differences, self-luminous displays, and color appearance specification.

Credit 3

PPHC-802 **Colorimetric Instrumentation and Standardization**

Registration #0923-802
This course covers current methods of precisely measuring the spectral properties of object colors and of radiation sources. Proper procedures in calibration, standardization, data analyses, instrument maintenance, and standards selection are discussed. The use of standard reference materials in optical metrology are explored. Various measurement assurance programs are introduced for the diagnostic evaluation of current colorimetric instrumentation.

Credit 4

PPHC 803 **Computer Colorant Formulation**

Registration #0923-803
his course explores modern methods of colorant forumulation prediction for the coloring of polymers, textiles, paper (impact and non-impact), and coatings. Emphasis is placed on Kubelka-Munk turbid media theory for opaque and translucent materials. Students have ample opportunity to familiarize themselves with several commercial computer colorant formulation systems.

Credit 3

PPHC-890 **Thesis**

Registration #0923-890
Thesis based on experimental evidence obtained by the candidate in an appropriate topic as arranged between the candidate and the director of the program.

Credit 9
(minimum for MS)

PPHC-899 **Independent Study**

Registration #0923-899
A student-proposed advanced project sponsored by a graduate faculty member. Approval required by the director of the program.

Credit variable

Munsell Color Science Laboratory (MCSL) Research and Education Equipment List

SPECTROPHOTOMETERS

Instrument Name	Features
Applied Color Systems Spectro-Sensor II ACS-1800ATE Color Matching and Batch Correction System	R. T; VIS Interfaced with IBM AT
Beckman DK2A	R, T; UV, VIS, IR
Diano Match Scan II	R, T; VIS, NIR Reversible Optics MCSL 0/45 Modification Interfaced with MCSL Timesharing System
Diano/Hardy Recording	R, T; VIS Small Area View Interfaced with MCSL Timesharing System
General Electric Recording	R, T; VIS Tristimulus Integrator
Hunterlab Labscan	R, T; VIS 0/45 Geometry Dedicated Computer for colorimetric calculations
IBM Model 9420	R, T; UV, VIS Analytical Instrument Integrating Sphere Attachment Dedicated Computer
Macbeth 1500	R, T; VIS Small Area View Dedicated Computer for Colorimetric Calculations
Milton Roy Color Scan Color Matching and Batch Correction System	R, T; VIS Quality Control System MatchPack I, II Interfaced with DEC PRO 350
MCSL Goniospectrophotometer	R, T; VIS Total Control of Illumination and Viewing Angles Interfaced with MCSL Timesharing System
Pacific Scientific Spectrogard Automatch Color Matching and Batch Correction System	R, T; VIS Small Area View Interfaced with Northstar Computer
Zeiss DMC-25	R, T, UV, VIS, IR Reversible Optics

COLORIMETERS

Instrument Name	Features
Hunterlab D25D2	R (45/0) XYZ, Hunter Lab
Hunterlab D25A9	R (45/0) XYZ, Yxy, Hunter Lab, CIELab, Color Differences, Dominant Wavelength, Purity Tappi Filter, Tappi Brightness
Minolta Chroma Meter I	R Yxy, CIELab
Minolta Chroma Meter II	R (45/0) Yxy, CIELab, Munsell HVC Interfaced with DP-100 Computer
Pacific Scientific Colorgard System 1000	R (0/45), T Small Area View XYZ, Yxy, CIELab Interfaced with Epson Computer

SPECTRORADIOMETERS

Instrument Name	Features
Minolta Chroma Meter II Incident	Incident Radiation Measurements Yxy, Yu'v', CCT, Illuminance Interfaced with DP-100 Computer
MCSL Spectroradiometer	PMT, Photodiode, Thermopile Calibrated Detector Interfaced with MCSL Timesharing System
Optronic Model 740	Calibrated Detector LED Sphere Attachment Detector Calibration Attachment Reflectance Attachment 280-1100 nm range Interfaced with MCSL Timesharing System
Tracor Northern DARSS	Array Radiometer 512 Detectors 240-870 nm range (also variable) Scan Times From 5 msec. Dedicated Mainframe Interfaced with MCSL Timesharing System

GLOSS METERS

Instrument Name	Features
Hunterlab Modular Model D48-7	20 and 60 degree heads
Hunterlab Dori-gon D47-6	Abridged Goniophotometer Distinctness of Image, Haze
Pacific Scientific Glossgard II	20, 60, 85 degree units

DENSITOMETERS

Instrument Name	Features
Cosar 75 CompuPlus	T, R (Cosar 76 head) Status A and Status M Responses
Cosar Pressmate I	R Status T Response
ESECO Speedmaster	T, R Status A and Status M Responses

VISUAL APPARATUS

Instrument Name	Features
Dianolite Viewing Booth (3)	Daylight, Tungsten, UV
Hilgor Ltd. Donaldson	T, Visual Colorimeter
Lovibond Tintometer Model E	R, T
Lovibond Tintometer Mark 3	R, T Fiber Optics
Macbeth	D50, A
Macbeth SpectraLight Viewing Booth	D65, CWF, Horizon, Narrow Band Fluorescent
Macbeth SpectraLight Viewing Booth	D75, CWF, Horizon, UV
Nagel Anomaloscope	

COMPUTERS

MCSL Timesharing System

CPU:	Digital Equipment Corp. PDP 11/73
Operating Systems:	RT11, TSX
Languages:	FORTRAN 77, Pascal, Macro
Memory:	1 Mb RAM
Mass Storage:	20 MB Fixed Disk
	2 Mb Floppy Disk
Video Terminals:	1 - Digital Equipment Corp. VT55 Graphicscope
	1 - Digital Equipment Corp. VT100 Decscope
	3 - Digital Equipment Corp. VT50 Decscope
	1 - Lear Seagler ADM3A Terminal
	1 - Visual 50 Terminal
	1 - Heath H-19 Terminal
Printers:	Digital Equipment Corp. LA100RA (with graphics)
	Digital Equipment Corp. Decwriter III
	Digital Equipment Corp. LQP02
Plotter:	Hewlitt Packard 7475 Digital XY Plotter

Heath H-11 Systems (3)

Operating System:	RT11
CPU:	Digital Equipment Corp. LSI-11/02
Memory:	64Kb RAM
Mass Storage:	0.5 Mb Floppy Disk

Personal Computers

2 Digital Equipment Corp. Rainbow 100's
1 IBM AT

Visual Determination of Color-Difference Ellipsoids using Probit Analysis

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A psychophysical experiment was performed in which pass-fail judgments were generated by means of paired comparison. The anchor pair was a near neutral of L*=50 with a total CIELAB color difference of $\Delta E^*=1$ along the vector from -a*+b*-L* to +a*-b*+L*. Samples were generated about 9 color centers including the 5 color centers recommended by the CIE Colour Difference technical committee in order to sample the representative surface-color range of CIELAB space. Samples geometrically increasing in color difference in 10 vector directions from each color center were produced using an acrylic enamel coating on aluminum panels. Sample pairs were fashioned which systematically increased in color difference in each vector direction from a $\Delta E^*=0.25$ to $\Delta E^*=3.5$. These sample pairs and anchor pair when in adjacency subtended a 10° visual angle as viewed by an observer adapted to a D_{65} simulator. 50 color-normal observers randomly viewed these sample pairs and made forced-choice pass or fail decisions comparing the magnitude of the color difference of the sample pair to the adjacent anchor pair. The sigmoidal frequency of rejection functions generated for each vector direction about a color center were transformed to a linear function by means of probit analysis, a statistical transformation based on the assumption the median (50%) pass fail point is centered at a gaussian distribution. Probit analysis is typically used in determining the median effective dosage in quantal experiments. The 50% point of the 10 vector directions were used to estimate tolerance ellipsoids for the 9 color centers.

The results of this experiment provide an important new data base of color difference tolerance ellipsoids. This data base has several advantages over tolerances generated by traditional scaling techniques. First, surface colors are used rather than aperture colors. Second, ellipsoids are generated at super-threshold levels representative of industrial color differences rather than sub-threshold levels typical of line elements or large differences typical of color order systems. Third, the visual task is expeditious enabling large numbers of observers to be used. Finally, probit analysis estimates both the tolerance and the uncertainty associated with each tolerance. This data base can be used as a field trial for existing color difference equations and as a basis for modeling new color difference equations.

*E.I. DuPont de Nemours & Company

Goniospectrophotometric Characteristics of White Reflectance Standards with respect to the CIE Normal/45 Geometry

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An experiment was performed to measure the goniospectrophotometric characteristics of several white standard reference materials within the CIE recommended view angle limits for normal/45 reflectance factor measurements. All measurements were made with normal illumination and view angles varying from 40° to 50°. This coincides with the current CIE recommendation which states that the view angle should be 45° ± 5°. The white materials investigated were pressed barium sulfate, pressed polytetrafluoroethylene (PTFE) powder, a white porcelain tile, and a pale gray ceramic tile (BCRA Series II). Pressed PTFE samples were prepared at two density levels, 1.0 and 2.5 g/cm^3. All of the samples are commonly used as transfer standards for bidirectional reflectance factor measurements.

The measurements were performed on the Munsell Color Science Laboratory Goniospectrophotometer. The photometric scale of the instrument was set using 0/45 spectral reflectance standards calibrated at the National Bureau of Standards. These standards consist of a set of BCRA Series II Ceramic Colour Standards and a white porcelain tile. The measurements were made with monochromatic illumination normal to the sample and view angles varying from 40° to 50° in 1° increments. The illumination and viewing angles can be controlled to within 5 minutes of arc. The illuminating beam has a half cone angle of 2.2° and illuminates a 1 cm square area of the sample. The half cone angle of the viewng beam is ~1.6° and a 3 mm diameter circular area of the sample is viewed.

An unacceptable amount of variation was found in the measured spectral reflectance factors of these samples over this range of view angles. Variations as great as 0.06 were found in the spectral reflectance factor measurements of the pressed barium sulfate and PTFE powder when the view angle was changed from 40° to 50°. The variation in luminous reflectance factor (D_{65}, 2°) for the barium sulfate and PTFE samples ranged from 0.03 to 0.04. The porcelain and ceramic tiles showed less variation; the luminous reflectance factor for these tiles changed about 0.02 as the angles were varied. These results indicate that the exact measurement geometries must be specified when inter-instrument comparisons are made for bidirectional reflectance factor measurements. The results are significant enough to warrant further investigation in two areas: the development of suitable transfer standards for bidirectional measurements and the currently recommended view angle limits for the normal/45 measurement geometry.

* The research on which this paper is based was directed by Franc Grum. Professor Grum died on Dec. 20, 1985; the present paper was written by Mr. Fairchild.