AL/HR-TR-1993-0172

AD-A277 204

COLORS IN NATURAL LANDSCAPES

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January 1994

Final Technical Report for Period January 1993 - April 1993

Approved for public release; distribution is unlimited.

AIR FORCE MATERIEL COMMAND
BROOKS AIR FORCE BASE, TEXAS

ARMSTRONG LABORATORY

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
January 1994

3. REPORT TYPE AND DATES COVERED
Final January 1993 - April 1993

4. TITLE AND SUBTITLE
Colors in Natural Landscapes

5. FUNDING NUMBERS
C - F33615-90-C-0005
PE - 62205F
PR - 1123
TA - 03
WU - 85

6. AUTHOR(S)
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Johannah A. Burnidge

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of Dayton Research Institute
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Dayton, OH 45469-0110

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Armstrong Laboratory (AFMC)
Human Resources Directorate
Aircrew Training Research Division
6001 S. Power Road, Bldg 558
Mesa, AZ 85206-0904

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AL/HR-TR-1993-0172

11. SUPPLEMENTARY NOTES
Armstrong Laboratory Technical Monitor: Dr. Elizabeth L. Martin, (602) 988-6561.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
This report supplies chromaticity coordinates and relative luminances of certain natural surfaces for which spectral reflectance distributions are presently available. Modelers of geographical databases for simulator displays may use this information to guide color selection for scene components. Where the reflectance data permit, relative luminances have also been computed for simulation of landscapes viewed through night vision devices.

14. SUBJECT TERMS
ANVIS; CATS EYE; Chromaticity; Computer-generated imagery; Luminance; Natural landscapes; Night vision simulation; RGB codes; Scene color; Spectral reflectance; Tristimulus values

15. NUMBER OF PAGES
24

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std Z39-18
298-102

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PREFACE

This report is written for programmers who create the geographical databases for computer-generated imagery in simulator displays. Assignment of colors to surfaces should be the least of their worries, yet they are often uncomfortably aware that the procedures they are using have grown up under the pressure of getting jobs done and lack a consistent rationale. Information about the colors of natural landscapes can be found in the color science literature, but programmers have no time to search this literature. Physical data needed for automatic computation of those colors can also be found, but no one has collected them in one place or summarized their meaning for computer-generated imagery.

The report emphasizes *relative luminances* of natural surfaces in addition to their chromaticity. The color assignment for a surface determines both the chromaticity and the range of lightnesses it can have in a daylight simulation. Because we have made use of reflectance data extending beyond the visible range into the near infrared, the tables in this report will also enable programmers to give proper attention to relative lightnesses in scenes intended for night-vision simulation.

This work was conducted by the University of Dayton Research Institute under Contract No. F33615-90-C-0005, Work Unit 1123-03-85. The authors wish to acknowledge the valuable assistance of the following individuals:

William C. Decker IV, now at the Electro-Optical Products Division of ITT in Roanoke, Virginia, who supplied the Lotus program from which some of the reflectance data and two of the sensitivity curves were taken,

Alex Firdman, who helped extract these data from the Lotus program,

Raymond L. Lee, Jr., Oceanography Department, U.S. Naval Academy, who called our attention to earlier literature on landscape colors,

Elizabeth Brummer, who helped set up the work sheets for our computations, and

Mrs. Marge Keslin, who edited, proofread, and typed the final manuscript.

COLORS IN NATURAL LANDSCAPES

INTRODUCTION

Visual displays of computer-generated imagery play an increasing role in the training of military and civilian aircrews. Stand-alone flight simulators bought by military units or commercial airlines commonly have the ability to display daytime as well as night imagery. Electronic networks have begun to link real-time simulators at widely scattered locations in order that military units of different types may join in exercises using a common geographical database.

The colors which appear in such a database depend more on the designers' preferences and local traditions than on color science. It has been generally assumed that the modeler should aim for "realism" in the choice of colors and that the best simulation is the one which most closely matches the appearance of the real world. No experimental evidence exists to support or reject this assumption. Before such evidence can be gathered, display colors must be brought under fairly precise control. Most simulator users have not yet achieved good color control, although simple methods of doing so are now readily available.

If the goal is realism, then the choice of color can be guided by computations based on physical data. The chromaticity and relative luminance of a surface are completely determined by the spectral reflectance distribution of that surface, the spectral energy distribution of its illumination, and the spatial relations of surface and source of illumination. Writers on computer graphics (Hall, 1988; Meyer & Greenberg, 1986) recommend that color selection be based on these physical data. Although they also provide references to articles containing such data, their recommendation has not had much impact on real-time computer-generated imagery, where modelers seek "realism" of colors more often by artistic judgment than by color science. Given the known facts about object colors picked from memory, it is not surprising that computer-generated images are more colorful than natural scenes. In memory, grass is greener, bricks are redder, and the sky is bluer, and most objects are remembered as having exaggerated saturation and lightness (Bartleson, 1960).

This article supplies reflectance-based chromaticity coordinates and relative luminances for surfaces prominent in natural landscapes. Not surprisingly, the chromaticities derived from colorimetric computations agree well with the chromaticities reported by Hendley and Hecht (1949), who determined landscape colors by visual matching with Munsell samples, and by Burton and Moorhead (1987), who studied digitized photographs of terrain scenes. Hendley and Hecht call attention to the fact that natural landscape colors have a limited hue gamut. "Green plants fall in a yellow-green region varying from 550 nm to 575 nm in dominant wavelength.[1] Earths and dried vegetation are yellow to orange-red (576 nm to 589 nm). Water, sky and distant objects are blue (459 nm to 486 nm)." In autumn, "vegetation covers not merely the summer range of green plants, but also that of earths, and extends beyond in the red to the end of the spectrum." The gamut is also limited with respect to saturation or colorimetric purity. Except for some autumn colors, most of the colors studied by Hendley and Hecht had excitation purity[2] less than 40%, declining to 11% or less at a viewing distance of 3.5 miles. With increased viewing distance, all colors also shifted toward blue. At distances 1.34 km and beyond, Burton and Morehead (1987) also found this shift toward a hue "indistinguishable from that of the sky" or, occasionally, slightly bluer than the sky.

These previous studies contain a few measures of daylight luminances, but the lightness information is not in a form readily usable by modelers. Since modelers of computer-generated imagery need information about the lightness as well as the chromaticity of scene elements, the present article also contains relative luminances computed from reflectance data. The luminance of a reflective surface, relative to the luminance of a perfect reflector in the same illumination, is commonly called the "luminance factor" (LF) of that surface. The tables presented here contain LF values for daylight (photopic) vision, unaided night (scotopic) vision, and two types of image-intensifiers currently used in night-vision goggles. Used with the equations supplied below, these tables of chromaticity and LF should be helpful to modelers who wish to achieve greater realism in simulator scenes and to ensure similarity of color among simulators operating at different geographical locations.

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[1]Dominant wavelength is determined relative to a reference white. In Hendley and Hecht (1949), the reference was Illuminant A (tungsten light), with a color temperature of about 2800° K. When both the reference white and the color in question have been plotted in a CIE chromaticity diagram, the straight line joining these points may be extended beyond the color to the spectrum locus or to the purple boundary. For a color lying between white and the spectrum locus, the intersection with the spectrum locus defines the color's dominant wavelength with respect to that reference white. For a color lying between white and the purple boundary, the intersection with the purple boundary defines the purest color of this hue. Since no single wavelength can be identified for this hue, it is customary to refer to such a color by stating the dominant wavelength of its *complementary color,* adding a negative sign. The complementary color lies at the intersection of the same straight line with the spectrum locus.

[2]Excitation purity is defined as the ratio, in the CIE 1931 chromaticity diagram, of the distance between a color and the reference white to the total distance between reference white and the color's dominant wavelength.

SOURCES OF REFLECTANCE DATA

Table 1 is based on a source of reflectance data which is well known to color scientists. Between 1930 and 1942, E. L. Krinov (1953) obtained spectral reflectance data on a large number of terrain surfaces in several geographical regions of the USSR, using various types of laboratory and field spectrographs available to him during that period. His report, published in 1946 from the Aero Methods Laboratory of the USSR Academy of Sciences, contains 370 reflectance distributions taken from about 150 different types of surfaces. Krinov grouped these "natural formations" into 8 categories: forests and shrubs, grass, mosses and lichens, field and garden crops, outcrops and soils, roads, water surfaces and snow, and buildings and building materials. Most of them were viewed from the ground; some were observed from the air at an altitude of about 300 m. In certain cases the same type of surface was measured several times in order to study variations due to season, moisture, sun angle, and viewing angle. Each measurement was recorded on a separate photographic plate, together with the reflectance from a standard plate in the same illumination. "The development of the many thousands of spectrograms was...a vast undertaking in which an entire collective of laboratory technicians and statisticians took part" (Krinov, 1953, p. 80).

The wavelengths from which recordings could be made were limited by the sensitivity of the photographic plates. To study the visible region of the spectrum, Krinov used Ilford panchromatic plates with sensitivity from 400-650 nm. At those times when he also measured infrared (IR) reflectance, he used one of several types of Agfa infrared plates sensitive to part of the range 700-1000 nm. The range between 650 and 700 nm was generally not studied, and in many cases the infrared portion of the reflectance file does not begin below 720 nm. The columns for unaided vision in Table 1 are computed from Krinov's reflectances in the 400-650 nm range. The columns for aided night vision are computed from the entire set of reflectances provided by Krinov, with values in the gap (between 650 and 700 nm or higher) interpolated by smoothing to connect the visible and infrared portions of the data.

Krinov's report is available in English through a translation prepared by E. Belkov and published by the National Research Council of Canada. Maloney (1986) and Maloney and Wandell (1986) have used his data to show that naturally occurring reflectance distributions may be described by a set of no more than four basis functions.

Table 2 is based on data supplied by William Decker and described in a paper written at the CECOM Center for Night Vision and Electro-Optics (Decker, 1989). Early in the 1970s, the Center undertook to develop methods for predicting the field performance of image intensifiers. This project required reflectivity data in the spectral region from 400 to 1200 nm, and some data of this kind were collected during that period. In the mid 1980s, Decker and his colleagues at the Center improved their prediction methods by obtaining additional reflectance data and measuring spectral attenuation coefficients for four relative humidities (0, 30, 60, and 90%). The

Table 1. Colorimetric Data Computed from Krinov Reflectances. Files are numbered and named as in Krinov (1953).

Krinov (files)	Surface	x (D65)	y (D65)	Photopic LF (D65)	Scotopic LF (moonlight)	ANVIS LF (moonlight)	CATS EYE LF (moonlight)
009	Birch	0.372	0.407	0.209	0.164		
010	Birch; full leaf	0.368	0.415	0.049	0.038	0.263	0.281
016	Oak	0.399	0.404	0.228	0.162		
023	Fur; full leaf	0.364	0.414	0.050	0.040		
025	Fir; late summer	0.324	0.363	0.031	0.029		
029	Linden; full leaf	0.346	0.415	0.081	0.067		
030	Linden; fall	0.390	0.386	0.064	0.048		
034	Juniper; full leaf	0.366	0.420	0.075	0.058	0.226	0.237
035	Alder; young leaf	0.363	0.417	0.067	0.052	0.329	0.352
037	Aspen; young, young	0.359	0.416	0.090	0.072	0.419	0.445
040	Aspen; mature, full	0.381	0.414	0.055	0.041	0.359	0.381
042	Aspen; fall	0.421	0.421	0.159	0.104		
048	Pine; mature, young	0.355	0.387	0.039	0.033	0.213	0.228
049	Pine; full leaf	0.342	0.368	0.045	0.040		
050	Weeds	0.368	0.388	0.037	0.030		
053	Heather	0.364	0.369	0.038	0.031	0.161	0.170
054	River valley	0.323	0.359	0.130	0.122	0.219	0.229
069	Reeds	0.343	0.395	0.096	0.081	0.370	0.398
070	Turf hillocks	0.383	0.430	0.033	0.024	0.174	0.185
072	River bank	0.338	0.354	0.143	0.132		
073	Alpine meadow	0.375	0.394	0.076	0.061	0.218	0.229
081	Pasture meadow	0.367	0.404	0.085	0.068		
084	Meadow; clover	0.367	0.410	0.135	0.106		
093	Meadow; daisies	0.351	0.383	0.125	0.106	0.412	0.438
094	Lush meadow	0.381	0.442	0.066	0.048	0.259	0.275
152	Duckweed	0.344	0.374	0.063	0.054	0.189	0.199
161	Grass; dusty	0.356	0.386	0.070	0.057	0.302	0.320
163	Grass; dry	0.366	0.381	0.110	0.090	0.285	0.296
171	Sphagnum moss	0.401	0.462	0.092	0.064	0.553	0.591

Table 1 (continued)

Krinov (files)	Surface	x (D65)	y (D65)	Photopic LF (D65)	Scotopic LF (moonlight)	ANVIS LF (moonlight)	CATS EYE LF (moonlight)
230	Ravine	0.344	0.358	0.350	0.314		
231	River bank; dry	0.343	0.358	0.218	0.195	0.316	0.324
232	Boulders; dry	0.319	0.343	0.219	0.216		
233	Boulders; wet	0.339	0.368	0.084	0.076		
234	Clay; dry	0.335	0.358	0.650	0.607		
235	Bottom reservoir	0.370	0.377	0.183	0.150	0.389	0.400
237	Silt; dry	0.308	0.321	0.188	0.197		
238	Conglomerate	0.372	0.366	0.231	0.188		
240	River bank; dry	0.339	0.355	0.145	0.133	0.254	0.263
241	Wind eroded; dry	0.370	0.368	0.231	0.188		
246	Shallows	0.338	0.359	0.108	0.098	0.162	0.167
247	Sand	0.347	0.361	0.276	0.245		
248	Sand dunes; no shadows	0.345	0.376	0.242	0.215	0.459	0.474
255	Sand dunes; shadows	0.356	0.385	0.277	0.238	0.250	0.248
268	Sandstone; red	0.381	0.376	0.232	0.182		
269	Sandstone; grey	0.330	0.354	0.598	0.568		
294	Soil; sandy, loam	0.343	0.362	0.113	0.102	0.138	0.139
302	Soil; grey, ploughed	0.349	0.359	0.051	0.044	0.135	0.143
313	Bare cliffs	0.345	0.383	0.278	0.255	0.261	0.260
322	Dirt Road; grey, podsol	0.341	0.357	0.099	0.088	0.170	0.176
325	Dirt Road; trampled	0.346	0.360	0.191	0.169	0.266	0.272
329	Road; paved with stone	0.361	0.378	0.193	0.163	0.322	0.329
333	Water; river, muddy	0.318	0.349	0.198	0.193	0.108	0.103
335	Water; reservoir, muddy	0.351	0.384	0.156	0.135	0.175	0.179
337	Fresh snow	0.303	0.326	0.769	0.795	0.672	0.667
348	Snow; dry, crusty	0.326	0.349	0.696	0.662	0.612	0.603
354	Snow with ice film	0.312	0.334	0.742	0.742	0.756	0.755

Table 1 (concluded)

Krinov (files)	Surface	x (D65)	y (D65)	Photopic LF (D65)	Scotopic LF (moonlight)	ANVIS LF (moonlight)	CATS EYE LF (moonlight)
355	Stones; dry	0.328	0.359	0.189	0.182		
356	Brick, red	0.411	0.372	0.205	0.141		
361	Bridge; wood, old, dark	0.332	0.367	0.268	0.249	0.362	0.372
363	Cobblestone street	0.342	0.367	0.262	0.238	0.300	0.303
365	Quay, granite	0.342	0.365	0.312	0.281	0.255	0.250
366	Asphalt	0.327	0.350	0.079	0.074		
368	Sidewalk; asphalt	0.347	0.370	0.243	0.216	0.172	0.166
370	Roof tile; new, red	0.379	0.390	0.197	0.157	0.645	0.673
176	Vetch	0.349	0.383	0.107	0.092		
180	Potatoes; drk green	0.342	0.390	0.083	0.070	0.265	0.285
181	White Clover	0.374	0.377	0.125	0.089		
182	Red Clover	0.382	0.364	0.121	0.086		
184	Corn	0.369	0.400	0.072	0.056		
185	Oats; spiked	0.336	0.415	0.075	0.063	0.609	0.653
192	Sunflower; in bloom	0.339	0.388	0.083	0.072	0.316	0.339
193	Oat Field; mowed	0.366	0.390	0.093	0.076		
202	Wheat	0.379	0.426	0.258	0.193		
209	Wheat; flowering	0.368	0.403	0.251	0.190		
212	Wheat; mowed	0.375	0.416	0.125	0.095	0.504	0.536
214	Winter Rye	0.344	0.384	0.170	0.147	0.477	0.508
216	Summer Rye	0.362	0.412	0.117	0.094		
221	Cotton	0.337	0.384	0.108	0.094	0.438	0.470
222	Cotton; flowering	0.303	0.399	0.082	0.080		

Table 2. Colorimetric Data Computed from Decker Reflectances. Files are numbered and named as in Decker's Lotus program.

Decker (files)	Surface	x (D65)	y (D65)	Photopic LF (D65)	Scotopic LF (moonlight)	ANVIS LF (moonlight)	CATS EYE (moonlight)
RA01	Desert Road Dirt	0.359	0.366	0.369	0.314	0.477	0.480
RA11	Sand/Gravel Road	0.357	0.371	0.234	0.201	0.282	0.283
RA26	Dirt Road, Dry(NVL)	0.415	0.394	0.185	0.128	0.318	0.321
RA37	Plywood	0.351	0.357	0.647	0.571	0.901	0.909
RA38	Dark Brown Pt	0.349	0.343	0.069	0.061	0.106	0.108
RA39	Lt Brown Pt	0.340	0.341	0.117	0.107	0.144	0.145
RA40	Concrete	0.335	0.352	0.361	0.335	0.412	0.414
RA41	Asphalt	0.344	0.355	0.127	0.115	0.179	0.181
RA16	Army Camouflg. Paint	0.332	0.361	0.058	0.054	0.219	0.231
RA17	Woodland Cam. Net	0.360	0.380	0.120	0.100	0.397	0.418
RA18	Desert Cam. Net	0.379	0.377	0.307	0.241	0.427	0.429
RA23	Army Sand (tan) Paint	0.370	0.375	0.367	0.297	0.431	0.430
RA27	Target, Brn, Card	0.388	0.382	0.271	0.212	0.536	0.546
RA28	Target, Grn, Card	0.331	0.353	0.098	0.092	0.107	0.108
RA31	German Cam. Net	0.347	0.408	0.099	0.086	0.345	0.364
RA32	Swedish Cam. Net	0.388	0.385	0.289	0.225	0.507	0.516
RB01	Desert Day BDU (pat8)	0.358	0.361	0.295	0.252	0.405	0.408
RB16	Syria, Camo Fabric	0.366	0.340	0.050	0.042	0.322	0.340
RB21	China, CBR Camo Unif	0.346	0.364	0.095	0.085	0.209	0.217
RB22	China, CBR Camo Unif 2	0.346	0.381	0.109	0.097	0.232	0.240
RB23	Std Desert Day BDU	0.365	0.357	0.194	0.161	0.342	0.346
RB26	Desert Day BDU (pat10)	0.365	0.372	0.300	0.252	0.433	0.437
RB27	Desert Cmbt Camo Coat	0.355	0.358	0.320	0.274	0.462	0.466
RB28	Desert Uniform (pat 2)	0.377	0.373	0.283	0.225	0.483	0.488
RB30	Perm Press Fatigues	0.344	0.374	0.095	0.084	0.171	0.176
RB31	Man in Fatigues	0.325	0.365	0.118	0.112	0.161	0.165
RB32	Man in Dress Unif	0.366	0.366	0.220	0.182	0.338	0.342
RB33	Winter BDU'S	0.350	0.371	0.096	0.085	0.375	0.396
RB34	Summer BDU'S	0.351	0.377	0.075	0.066	0.286	0.300
RB35	Gray Flt Suit	0.320	0.354	0.098	0.098	0.421	0.447
RB38	USCG Blul Fs	0.197	0.202	0.041	0.070	0.387	0.416
RB39	USCG Oran Fs	0.514	0.367	0.232	0.092	0.672	0.678

Table 2 (concluded)

Decker (files)	Surface	x (D65)	y (D65)	Photopic LF (D65)	Scotopic LF (moonlight)	ANVIS LF (moonlight)	CATS EYE (moonlight)
RA02	Desert Bush	0.352	0.362	0.221	0.195	0.314	0.317
RA06	Pine Bark-NVL	0.357	0.356	0.083	0.072	0.187	0.192
RA12	Green Foliage	0.342	0.420	0.124	0.105	0.517	0.553
RA13	Pine Needles(grn)	0.338	0.407	0.080	0.068	0.424	0.455
RA15	Maple Tree Bark-NVL	0.342	0.349	0.089	0.081	0.178	0.183
RA25	Sm Twigs/Leaves-AZ	0.377	0.375	0.134	0.108	0.257	0.262
RA30	Desert Bush Bark	0.340	0.351	0.135	0.124	0.270	0.278
RA33	Twigs/Flwr-AZ	0.396	0.390	0.147	0.112	0.295	0.301
RA34	Twigs/Sm-AZ	0.340	0.381	0.215	0.194	0.463	0.485
RA35	Brn Twigs/Lv-AZ	0.395	0.382	0.049	0.037	0.172	0.179
RA36	LBrn Twig/Lv-AZ	0.340	0.349	0.061	0.056	0.100	0.102
RA09	Green Grass	0.339	0.410	0.102	0.087	0.511	0.548
RA10	Dead Grass	0.376	0.383	0.270	0.221	0.497	0.508
RA07	Mustard Leaves/Stems	0.361	0.441	0.196	0.156	0.520	0.553
RA08	Green Corn Leaf	0.338	0.418	0.115	0.097	0.404	0.433
RA03	Desert Gravel	0.364	0.366	0.198	0.166	0.264	0.266
RA04	Alabama Red Clay	0.446	0.375	0.072	0.043	0.173	0.176
RA05	Sandy Soil-Ocean Cty	0.360	0.368	0.132	0.113	0.209	0.213
RA14	Dry Sand-Ocean City	0.344	0.357	0.325	0.293	0.400	0.402
RA24	Mixed Soil	0.362	0.362	0.065	0.055	0.135	0.139
RA42	Light Rock-AZ	0.349	0.358	0.334	0.295	0.405	0.407
RA43	Dark Rock-AZ	0.350	0.357	0.172	0.151	0.216	0.217
RA44	Sand Dunes-AZ	0.364	0.366	0.140	0.117	0.174	0.175
RA45	Rocks&Soil-AZ	0.367	0.367	0.231	0.192	0.315	0.317
RA46	Heavy Clay	0.402	0.383	0.127	0.093	0.237	0.241
RA47	Soil Mix 1	0.396	0.381	0.130	0.097	0.237	0.240
RA48	Soil Mix 2	0.364	0.363	0.057	0.048	0.127	0.131
RA22	Saudi White Sand	0.406	0.383	0.222	0.16	0.418	0.423
RC13	Top Soil Mix	0.362	0.362	0.060	0.051	0.131	0.135

reflectances were collected with a Perkin-Elmer Lambda 9 Spectrophotometer; the atmospheric transmission data were obtained from LOWTRAN VI.

Decker has not published these data; they are provided to users as part of a Lotus program which computes target/background contrasts for several types of NVDs under a variety of viewing conditions. Almost 100 reflectance distributions are supplied in this program, but about half of them describe the reflectance of military vehicles and uniforms. These distributions cover the range from 400 to at least 1200 nm (and in most cases to 2000 nm) at 10-nm intervals. Data in Table 2 for unaided vision have been computed from Decker's data in the range 400-700 nm. Data for aided vision with ANVIS or CATS EYE goggles have been computed over the range 400-900 nm using the sensor response curves which were also incorporated into the Lotus program.

COMPUTED CHROMATICITY OF SURFACES IN DAYLIGHT

Figure 1 shows the location in CIE 1976 Uniform Chromaticity Space (UCS) for [illegible] of the Krinov and 59 of the Decker surfaces under daylight (D65) illumination. The surfaces are grouped according to type. These chromaticity coordinates are based on XYZ tristimulus values computed from each spectral reflectance distribution according to the equation

$$T = \Sigma\, R(\lambda)\, E_t(\lambda), \qquad (1)$$

where T is a tristimulus value (X, Y, or Z), $R(\lambda)$ is the reflectance of the surface at wavelength lambda, and $E_t(\lambda)$ is the relative spectral energy distribution of D65 daylight at that wavelength, weighted by the appropriate CIE 1964 large-field color-matching function $\bar{x}$, $\bar{y}$, or $\bar{z}$. Values of $E_t(\lambda)$ were taken from Table IV (3,3,8) of Wyszecki & Stiles (1982, pp. 774-775), where the tabled values have been normalized to give Y = 100 for a perfect reflector. Therefore, the Y tristimulus value computed for any surface, when divided by 100, gives the LF for that surface.

Chromaticity coordinates are computed from the XYZ tristimulus values by the following equations:

$$x = X/(X + Y + Z), \qquad (2)$$

$$y = Y/(X + Y + Z), \qquad (3)$$

$$u' = 4X/(X + 15Y + 3Z), \text{ and} \qquad (4)$$

$$v' = 9Y/(X + 15Y + 3Z), \qquad (5)$$

where x and y are the chromaticity coordinates in the CIE 1931 chromaticity diagram and u' and v' are the corresponding coordinates in the CIE 1976 UCS.

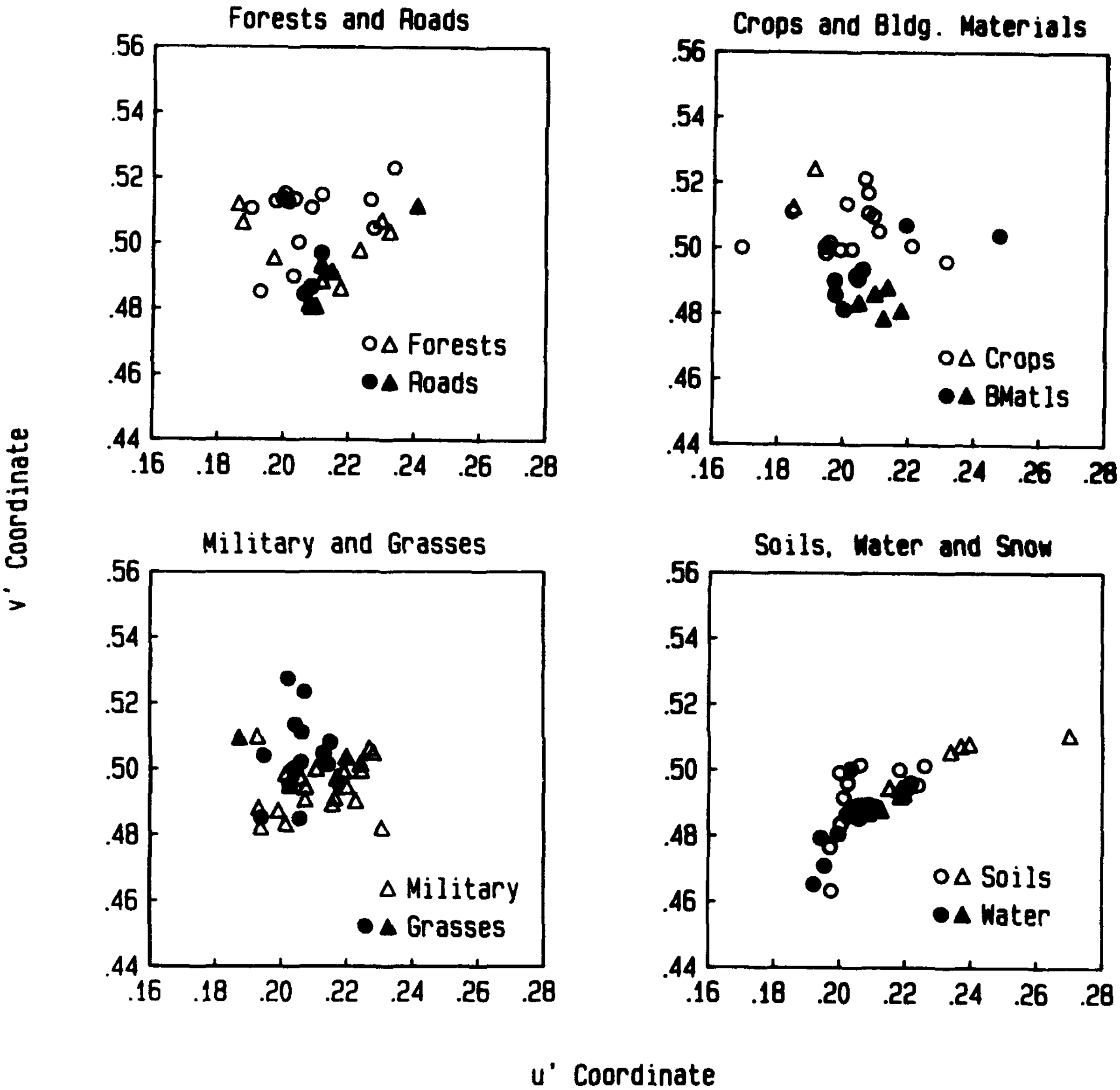

Figure 1
Chromaticity of Natural Surfaces. Computed from Krinov (circles) and Decker (triangles) reflectance data and displayed in CIE 1976 Uniform Chromaticity Space.

The region enlarged in Figure 1 appears again in Figure 2, where it can be compared to the locus of spectral colors and to the color gamut available in typical CRT displays. Two of the Decker colors (US Coast Guard orange and blue) do not appear in Figure 1; they are plotted in Figure 2. It is clear from Figure 2 that all the colors in Figure 1 lie within a region easily achievable by full-color electronic displays of any type.

LUMINANCE FACTORS FOR DAY AND NIGHT VISION

Color selection involves specifying not only the chromaticity coordinates but also the relative luminance for each surface. Variations in luminance due to shading, texture, or orientation will be computed in real time by the image generator. The database color table provides a starting point for these computations as a set of three numbers, the "RGB code," which specify the voltages for the red, green, and blue components in the absence of shading or texture effects. The relative luminance of surfaces in the scene is fully as important as their chromaticity. Indeed, it may even be more important, since rapid detection of high spatial frequency content in a scene depends principally upon luminance rather than color differences.

Changing the luminance of a scene component requires changing all three numbers in the RGB code, and the changes needed are rarely simple proportions for each number. When a modeler thinks of color habitually in RGB terms, it is hard to give proper attention to luminance differences in a scene. Thinking in XYZ terms makes such attention easy; since luminance information is carried by the Y tristimulus value, relative Y values give relative luminances for any group of scene components. Adjustments in Y values, accompanied by proportional adjustments in the X and Z values, will always adjust luminance without changing chromaticity.

This point can be illustrated by considering some values in Table 1, based on reflectances from the Krinov data set. If the luminance scale available in a display ranges from 0 to 100 cd/m^2, the XYZ values in this table will give realistic chromaticities and relative luminances without any adjustment. A granite structure at 31.2 cd/m^2 will have about half the luminance of a patch of dry clay (65 cd/m^2) and about 1.5 times the luminance of a red roof. Indeed, if the scene is restricted to the components in this table, the XYZ values can be used without adjustment when the display can produce no output greater than about 70 cd/m^2, since the highest Y-value in the table is 65.0 and the chromaticity for that value is close to an equal-energy white ($x = y = .33$).

But displays are likely to differ in their range of luminance output. In order to use the available range most efficiently, the modeler may set the luminance of the brightest surface in the scene to the Y-value of the maximum luminance the display can produce <u>at that chromaticity.</u> Then all other Y-values in the daylight scene may be

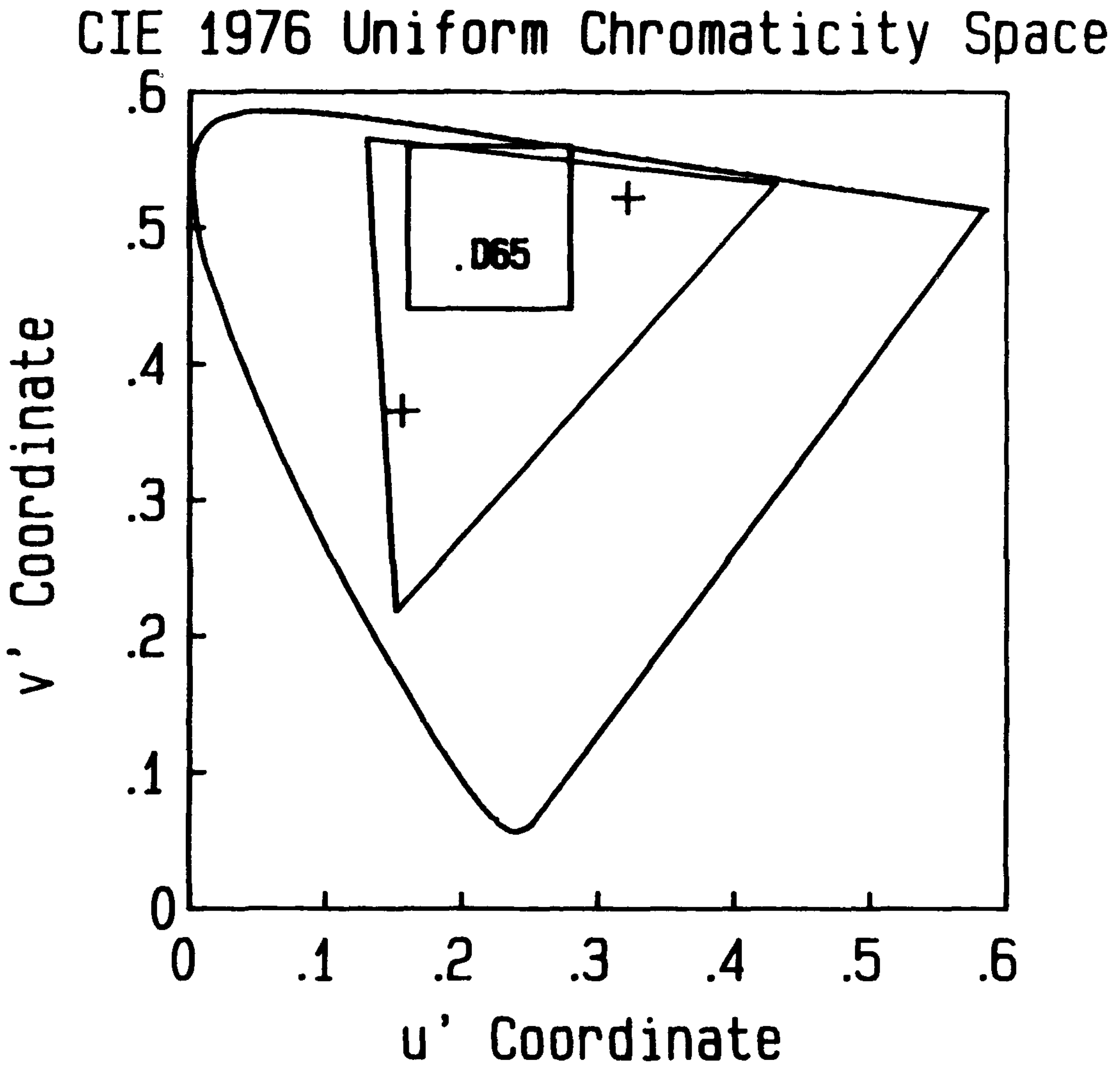

Figure 2
Spectrum Locus and Purple Boundary in CIE 1976 Uniform Chromaticity Space. Region enlarged in Figure 1 is shown here as a square containing the locus of D65 daylight. Triangle inside the spectrum locus represents the maximum color gamut for a typical color CRT. Chromaticities for the US Coast Guard Blue and Orange colors, included in Table 2, could not be shown in Figure 1 and are indicated here by crosses.

adjusted according to their luminance factors, given in the column LF, in relation to the Y and LF of the brightest surface. After X and Z values are adjusted proportionally to the new Y values, the RGB luminances for each surface can be generated from the equation

$$\begin{pmatrix} LR \\ LG \\ LB \end{pmatrix} = M^{-1} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}, \qquad (6)$$

where LR, LG, and LB are the RGB luminances and M^{-1} is the inverse of the chromaticity matrix M describing the display primaries,

$$M = \begin{vmatrix} xR/yR & xG/yG & xB/yB \\ 1 & 1 & 1 \\ zR/yR & zG/yG & zB/yB \end{vmatrix}. \qquad (7)$$

The x-, y-, and z-chromaticity coordinates of the primaries R, G, and B at maximum voltage can be taken as approximations to the values of xR, yR,....zB, even though, in fact, the matrix M will vary somewhat, depending on the voltage producing the required luminances.

Luminance factors have also been computed for night vision, and these values are included in Tables 1 and 2. To obtain these factors, the relative spectral energy distribution for daylight was again used, on the assumption that the distribution of night illumination in the visible range is not significantly different from the daylight distribution. However, for unaided night vision, the daylight distribution was weighted by the function $V'(\lambda)$, the scotopic sensitivity function for human vision, and normalized to give $Y = 100$ for a perfect reflector. The scotopic LF values for neutral surfaces do not differ much from the daylight values; reds and yellows decline in brightness relative to greens, as would be expected from the Purkinje effect.

Tables 1 and 2 provide additional information on relative effectiveness of these surfaces in stimulating ANVIS and CATS EYE night vision goggles. These data can be used as luminance factors for simulating the appearance of a scene when viewed through these NVDs. Note that daylight LFs in this table range from 0.04 to 0.65; ANVIS LFs range from 0.1 to 0.9.

CONCLUSION

If flight simulator displays are provided with colors and relative luminances closely similar to those in the natural landscape, will pilot performance improve? Will pilots find the displays more acceptable, or will they, perhaps, prefer displays in which the colors are "richer than life?" Are there some training purposes which might best be served by departing from the colors of nature, at least for certain classes of objects represented in the display? None of these questions has been addressed in this report. Indeed, no research relevant to these questions has yet been performed, largely because simulator users have only recently begun to apply color science technology to the control of display color.

Nevertheless, there is a tacit assumption--yet to be tested in controlled experiments--that a closer approximation to realism means an improvement in simulation. The assumption seems particularly appropriate to simulations which are intended for use in military mission rehearsal. This report presents the necessary data for realistic chromaticities and lightnesses. If it encourages the simulator community to give such realism a real trial, the report will have served its purpose.

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