ÖZET

NESNE AYDINLATILMASINDA YENİ BİR YÖNTEM

YÜZEY KROMATİSİTE KOORDİNATLARININ LED TABANLI AYDINLATILMA ARACI OLARAK MÜZELERDE KULLANIMI

Ekrem Erhan DİKEL

Güzel Sanatlar, Tasarım ve Mimarlık Fakültesi Doktora

Tez Yöneticisi: Doç. Dr. Cengiz YENER

Eylül, 2007

Günümüz çağdaş müze aydınlatılmasında uygun renksel geriverim ve renk sıcaklığı değerlerine sahip, aynı zamanda tayfsal dağılımında kızıl üstü ve mor altı dalga boyları içermeyen ışık kaynağı seçilmektedir. Ancak ışık kaynaklarının genellikle göz ardı edilen bir diğer önemli özelliği olan kromatisite koordinatları hiçbir tabloda yol gösterici olarak ışık tasarımcısı ya da küratörlerin kullanımına açılmamıştır. Bu çalışma, eserlerin yüzey renklerinin kromatisite koordinatları ile, seçilecek ışık kaynağının kromatisite koordinatları arasında bir ilişkilendirme kurmayı ve gelecekteki müze aydınlatmalarında yol gösterici bir yöntem oluşturmayı hedeflemektedir. Bunun için, geleceğin ışık kaynağı gözüyle bakılan Işık Yayan Diyot (Light Emitting Diode) LED teknolojisi incelenmiş, seçilen örneklerin aydınlatılmasında bilgisayar destekli aydınlatma yöntemleri kullanılarak bir deney düşünülmüştür. Çalışmada, renkli nesnelerin kromatisite koordinatlarına göre özel olarak üretilen ve aydınlatma uygulamalarında sıkça kullanılan 3000, 4200 ve 6500 Kelvin renk sıcaklığına sahip ışık kaynakları altındaki görünümleri referans ışık kaynağı olarak kabul edilen D65'in altındaki görünümleri ile kıyaslanmış ve deneklerden çeşitli değerlendirmeler yapmaları istenmiştir. Yapılan deneyin sonucunda; yüzey renkleriyle aynı kromatisite koordinatlarına sahip ışıkla aydınlatılan nesnelerin denekler tarafından daha çok tercih edildiği görülmüştür. Çalışma, çağdaş müzecilik uygulamalarında ışık kaynağı seçimine yönelik yol gösterme özelliği ile literatüre katkı sağlamaktadır.

Anahtar Sözcükler: Kromatisite Koordinatları, LED, Müze Aydınlatması

ABSTRACT

A NEW METHOD IN OBJECT LIGHTING

USING SURFACE CHROMATICITY COORDINATES
AS A LED-BASED LIGHTING TOOL
IN MUSEUMS

Ekrem Erhan DİKEL
Ph.D. in Art, Design, and Architecture
Supervisor: Assoc. Prof. Dr. Cengiz YENER
September, 2007

In contemporary museum lighting, the common practice is to choose light sources with recommended Color Rendering Indices (CRI) and Color Temperatures (CT) that do not emit harmful wavelengths: ultraviolet and infrared. In addition to CRI and CT, the commonly disregarded component of each light source, the Chromaticity Coordinates (CC), do not exist in any guidelines that are intended to be used by museum lighting designers and curators. This thesis aims to create a guideline for the museum lighting designers by proposing a new lighting method based on the relation between the surface CC of the museum objects and the CC of the light sources that are proposed to be their illuminators. For this reason, an experiment was conducted by using the Light-Emitting Diodes (LEDs) and computerized lighting controlled systems to test the validity of the proposed method. In the study, the appearances of the colored objects under a D65 reference light source were evaluated by comparing the created light source with their CC values and three other LED light sources with CT of 3000, 4200, and 6500 Kelvin that are mainly used in the museum lighting design applications. The results of the experiment showed that subjects preferred the appearance of the objects under lights that have same CC as the object. This thesis contributes to the museum lighting literature by creating the basis for a guideline for choosing and creating unique light sources for objects, by using their own physical properties.

Keywords: Chromaticity Coordinates, Light Emitting Diodes (LED), Museum Lighting

Pair 38	S_7_1 - S_7_3	.559	1.481	.254	.042	1.076	2.200	33	.035
Pair 39	S_7_1 - S_7_4	1.559	1.691	.290	.969	2.149	5.375	33	.000
Pair 40	S_7_2 - S_7_3	-1.206	1.473	.253	-1.720	-.692	-4.775	33	.000
Pair 41	S_7_2 - S_7_4	-.206	1.572	.270	-.754	.343	-.764	33	.451
Pair 42	S_7_3 - S_7_4	1.000	1.073	.184	.626	1.374	5.434	33	.000
Pair 43	S_8_1 - S_8_2	2.206	1.038	.178	1.844	2.568	12.391	33	.000
Pair 44	S_8_1 - S_8_3	.912	1.422	.244	.416	1.408	3.739	33	.001
Pair 45	S_8_1 - S_8_4	1.118	1.493	.256	.597	1.638	4.366	33	.000
Pair 46	S_8_2 - S_8_3	-1.294	1.244	.213	-1.728	-.860	-6.066	33	.000
Pair 47	S_8_2 - S_8_4	-1.088	1.379	.236	-1.569	-.607	-4.602	33	.000
Pair 48	S_8_3 - S_8_4	.206	1.298	.223	-.247	.659	.925	33	.362

APPENDIX G.3: Paired T-Tests for Saturation.

Table G.3. Paired Samples Test for Saturation.

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	S_1_1 - S_1_2	1.794	1.274	.218	1.350	2.239	8.212	33	.000
Pair 2	S_1_1 - S_1_3	.324	1.492	.256	-.197	.844	1.265	33	.215
Pair 3	S_1_1 - S_1_4	.588	1.844	.316	-.055	1.232	1.860	33	.072
Pair 4	S_1_2 - S_1_3	-1.471	1.237	.212	-1.902	-1.039	-6.934	33	.000
Pair 5	S_1_2 - S_1_4	-1.206	1.250	.214	-1.642	-.770	-5.625	33	.000
Pair 6	S_1_3 - S_1_4	.265	1.639	.281	-.307	.836	.942	33	.353
Pair 7	S_2_1 - S_2_2	1.794	.880	.151	1.487	2.101	11.887	33	.000
Pair 8	S_2_1 - S_2_3	.559	1.481	.254	.042	1.076	2.200	33	.035
Pair 9	S_2_1 - S_2_4	.941	1.808	.310	.310	1.572	3.035	33	.005
Pair 10	S_2_2 - S_2_3	-1.235	1.281	.220	-1.682	-.788	-5.625	33	.000
Pair 11	S_2_2 - S_2_4	-.853	1.654	.284	-1.430	-.276	-3.007	33	.005
Pair 12	S_2_3 - S_2_4	.382	1.724	.296	-.219	.984	1.294	33	.205
Pair 13	S_3_1 - S_3_2	1.853	1.132	.194	1.458	2.248	9.547	33	.000
Pair 14	S_3_1 - S_3_3	1.059	1.434	.246	.558	1.559	4.305	33	.000
Pair 15	S_3_1 - S_3_4	.824	1.660	.285	.244	1.403	2.893	33	.007
Pair 16	S_3_2 - S_3_3	-.794	1.366	.234	-1.271	-.318	-3.390	33	.002
Pair 17	S_3_2 - S_3_4	-1.029	1.586	.272	-1.583	-.476	-3.786	33	.001
Pair 18	S_3_3 - S_3_4	-.235	1.634	.280	-.805	.335	-.840	33	.407
Pair 19	S_4_1 - S_4_2	.647	1.346	.231	.178	1.117	2.804	33	.008
Pair 20	S_4_1 - S_4_3	-.588	1.635	.280	-1.159	-.018	-2.098	33	.044
Pair 21	S_4_1 - S_4_4	-.824	1.898	.326	-1.486	-.161	-2.529	33	.016
Pair 22	S_4_2 - S_4_3	-1.235	1.415	.243	-1.729	-.741	-5.089	33	.000
Pair 23	S_4_2 - S_4_4	-1.471	1.461	.251	-1.980	-.961	-5.868	33	.000
Pair 24	S_4_3 - S_4_4	-.235	1.776	.305	-.855	.384	-.772	33	.445
Pair 25	S_5_1 - S_5_2	2.324	.768	.132	2.056	2.591	17.652	33	.000
Pair 26	S_5_1 - S_5_3	.765	1.156	.198	.361	1.168	3.856	33	.001
Pair 27	S_5_1 - S_5_4	1.647	1.252	.215	1.210	2.084	7.668	33	.000
Pair 28	S_5_2 - S_5_3	-1.559	.991	.170	-1.904	-1.213	-9.176	33	.000
Pair 29	S_5_2 - S_5_4	-.676	1.224	.210	-1.104	-.249	-3.223	33	.003
Pair 30	S_5_3 - S_5_4	.882	1.274	.218	.438	1.327	4.040	33	.000
Pair 31	S_6_1 - S_6_2	1.353	1.203	.206	.933	1.773	6.557	33	.000
Pair 32	S_6_1 - S_6_3	-.176	1.783	.306	-.799	.446	-.577	33	.568
Pair 33	S_6_1 - S_6_4	-.471	1.674	.287	-1.055	.113	-1.639	33	.111
Pair 34	S_6_2 - S_6_3	-1.529	1.354	.232	-2.002	-1.057	-6.588	33	.000
Pair 35	S_6_2 - S_6_4	-1.824	1.114	.191	-2.212	-1.435	-9.546	33	.000
Pair 36	S_6_3 - S_6_4	-.294	1.426	.244	-.792	.203	-1.203	33	.238
Pair 37	S_7_1 - S_7_2	1.765	1.075	.184	1.390	2.140	9.574	33	.000

Pair 38	B_7_1 - B_7_3	.529	1.285	.220	.081	.978	2.403	33	.022
Pair 39	B_7_1 - B_7_4	1.471	1.502	.258	.946	1.995	5.708	33	.000
Pair 40	B_7_2 - B_7_3	-1.588	1.184	.203	-2.001	-1.175	-7.824	33	.000
Pair 41	B_7_2 - B_7_4	-.647	1.495	.256	-1.169	-.125	-2.524	33	.017
Pair 42	B_7_3 - B_7_4	.941	1.127	.193	.548	1.334	4.871	33	.000
Pair 43	B_8_1 - B_8_2	2.235	1.075	.184	1.860	2.610	12.127	33	.000
Pair 44	B_8_1 - B_8_3	1.029	1.446	.248	.525	1.534	4.152	33	.000
Pair 45	B_8_1 - B_8_4	1.324	1.093	.187	.942	1.705	7.059	33	.000
Pair 46	B_8_2 - B_8_3	-1.206	1.225	.210	-1.633	-.778	-5.738	33	.000
Pair 47	B_8_2 - B_8_4	-.912	1.357	.233	-1.385	-.438	-3.919	33	.000
Pair 48	B_8_3 - B_8_4	.294	1.528	.262	-.239	.827	1.122	33	.270

APPENDIX G.2: Paired T-Tests for Brightness.

Table G.2. Paired Samples Test for Brightness.

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	B_1_1 - B_1_2	1.706	1.219	.209	1.280	2.131	8.158	33	.000
Pair 2	B_1_1 - B_1_3	.853	1.459	.250	.344	1.362	3.408	33	.002
Pair 3	B_1_1 - B_1_4	1.559	1.618	.277	.994	2.123	5.618	33	.000
Pair 4	B_1_2 - B_1_3	-.853	1.395	.239	-1.340	-.366	-3.564	33	.001
Pair 5	B_1_2 - B_1_4	-.147	1.690	.290	-.737	.443	-.507	33	.615
Pair 6	B_1_3 - B_1_4	.706	1.426	.244	.208	1.203	2.887	33	.007
Pair 7	B_2_1 - B_2_2	1.765	1.046	.179	1.400	2.130	9.836	33	.000
Pair 8	B_2_1 - B_2_3	.794	1.452	.249	.288	1.301	3.189	33	.003
Pair 9	B_2_1 - B_2_4	1.206	1.719	.295	.606	1.806	4.089	33	.000
Pair 10	B_2_2 - B_2_3	-.971	1.425	.244	-1.468	-.474	-3.973	33	.000
Pair 11	B_2_2 - B_2_4	-.559	1.709	.293	-1.155	.037	-1.907	33	.065
Pair 12	B_2_3 - B_2_4	.412	1.635	.280	-.159	.982	1.468	33	.151
Pair 13	B_3_1 - B_3_2	1.765	1.046	.179	1.400	2.130	9.836	33	.000
Pair 14	B_3_1 - B_3_3	.794	1.737	.298	.188	1.400	2.666	33	.012
Pair 15	B_3_1 - B_3_4	.618	1.843	.316	-.025	1.261	1.955	33	.059
Pair 16	B_3_2 - B_3_3	-.971	1.359	.233	-1.445	-.496	-4.164	33	.000
Pair 17	B_3_2 - B_3_4	-1.147	1.438	.247	-1.649	-.645	-4.650	33	.000
Pair 18	B_3_3 - B_3_4	-.176	1.604	.275	-.736	.383	-.641	33	.526
Pair 19	B_4_1 - B_4_2	.529	1.354	.232	.057	1.002	2.280	33	.029
Pair 20	B_4_1 - B_4_3	-.441	1.795	.308	-1.068	.185	-1.433	33	.161
Pair 21	B_4_1 - B_4_4	-.765	1.908	.327	-1.430	-.099	-2.337	33	.026
Pair 22	B_4_2 - B_4_3	-.971	1.527	.262	-1.503	-.438	-3.706	33	.001
Pair 23	B_4_2 - B_4_4	-1.294	1.605	.275	-1.854	-.734	-4.700	33	.000
Pair 24	B_4_3 - B_4_4	-.324	1.683	.289	-.911	.264	-1.121	33	.270
Pair 25	B_5_1 - B_5_2	2.147	.989	.170	1.802	2.492	12.661	33	.000
Pair 26	B_5_1 - B_5_3	.765	1.350	.231	.294	1.236	3.304	33	.002
Pair 27	B_5_1 - B_5_4	1.559	1.440	.247	1.057	2.061	6.314	33	.000
Pair 28	B_5_2 - B_5_3	-1.382	1.074	.184	-1.757	-1.008	-7.509	33	.000
Pair 29	B_5_2 - B_5_4	-.588	1.438	.247	-1.090	-.087	-2.385	33	.023
Pair 30	B_5_3 - B_5_4	.794	1.298	.223	.341	1.247	3.569	33	.001
Pair 31	B_6_1 - B_6_2	1.294	1.219	.209	.869	1.720	6.189	33	.000
Pair 32	B_6_1 - B_6_3	.059	1.740	.298	-.548	.666	.197	33	.845
Pair 33	B_6_1 - B_6_4	-.529	1.813	.311	-1.162	.103	-1.703	33	.098
Pair 34	B_6_2 - B_6_3	-1.235	1.327	.228	-1.698	-.772	-5.428	33	.000
Pair 35	B_6_2 - B_6_4	-1.824	1.336	.229	-2.290	-1.357	-7.956	33	.000
Pair 36	B_6_3 - B_6_4	-.588	1.373	.236	-1.067	-.109	-2.498	33	.018
Pair 37	B_7_1 - B_7_2	2.118	.844	.145	1.823	2.412	14.623	33	.000

Pair 23	H_4_2 - H_4_4	-2.029	1.425	.244	-2.526	-1.532	-8.307	33	.000
Pair 24	H_4_3 - H_4_4	-.618	1.181	.203	-1.030	-.206	-3.049	33	.004
Pair 25	H_5_1 - H_5_2	2.471	.748	.128	2.210	2.732	19.256	33	.000
Pair 26	H_5_1 - H_5_3	1.147	.610	.105	.934	1.360	10.971	33	.000
Pair 27	H_5_1 - H_5_4	2.147	.925	.159	1.824	2.470	13.528	33	.000
Pair 28	H_5_2 - H_5_3	-1.324	1.065	.183	-1.695	-.952	-7.245	33	.000
Pair 29	H_5_2 - H_5_4	-.324	1.273	.218	-.768	.120	-1.482	33	.148
Pair 30	H_5_3 - H_5_4	1.000	.853	.146	.702	1.298	6.837	33	.000
Pair 31	H_6_1 - H_6_2	1.706	.906	.155	1.390	2.022	10.985	33	.000
Pair 32	H_6_1 - H_6_3	.824	1.218	.209	.399	1.248	3.943	33	.000
Pair 33	H_6_1 - H_6_4	-.294	1.661	.285	-.874	.285	-1.032	33	.309
Pair 34	H_6_2 - H_6_3	-.882	1.149	.197	-1.283	-.482	-4.480	33	.000
Pair 35	H_6_2 - H_6_4	-2.000	1.557	.267	-2.543	-1.457	-7.490	33	.000
Pair 36	H_6_3 - H_6_4	-1.118	1.343	.230	-1.586	-.649	-4.852	33	.000
Pair 37	H_7_1 - H_7_2	2.882	.409	.070	2.740	3.025	41.059	33	.000
Pair 38	H_7_1 - H_7_3	.941	.547	.094	.750	1.132	10.029	33	.000
Pair 39	H_7_1 - H_7_4	1.941	.600	.103	1.732	2.151	18.863	33	.000
Pair 40	H_7_2 - H_7_3	-1.941	.343	.059	-2.061	-1.821	-33.000	33	.000
Pair 41	H_7_2 - H_7_4	-.941	.547	.094	-1.132	-.750	-10.029	33	.000
Pair 42	H_7_3 - H_7_4	1.000	.426	.073	.851	1.149	13.675	33	.000
Pair 43	H_8_1 - H_8_2	2.471	.706	.121	2.224	2.717	20.391	33	.000
Pair 44	H_8_1 - H_8_3	1.471	1.022	.175	1.114	1.827	8.390	33	.000
Pair 45	H_8_1 - H_8_4	1.118	1.175	.201	.708	1.527	5.548	33	.000
Pair 46	H_8_2 - H_8_3	-1.000	1.181	.202	-1.412	-.588	-4.939	33	.000
Pair 47	H_8_2 - H_8_4	-1.353	1.276	.219	-1.798	-.908	-6.181	33	.000
Pair 48	H_8_3 - H_8_4	-.353	1.346	.231	-.822	.117	-1.529	33	.136

APPENDIX G

DATA STRUCTURES[17]

APPENDIX G.1: Paired T-Tests for Hue.

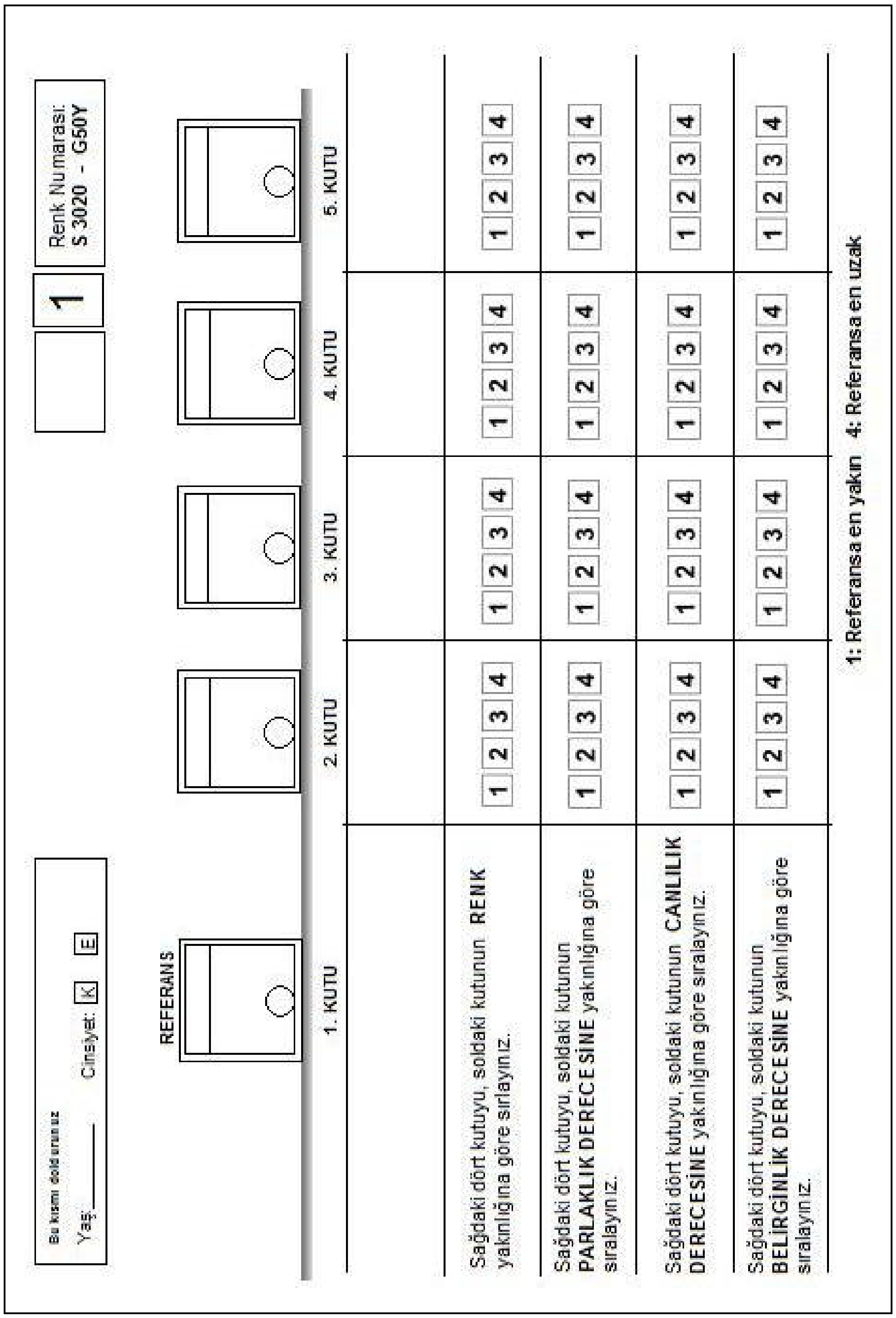
Table G.1. Paired Samples Test for Hue.

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Dev.	Std. Error Mean	95% Confidence Interval of the Difference				
					Lower	Upper			
Pair 1	H_1_1 - H_1_2	2.588	.657	.113	2.359	2.817	22.978	33	.000
Pair 2	H_1_1 - H_1_3	1.118	.591	.101	.911	1.324	11.025	33	.000
Pair 3	H_1_1 - H_1_4	2.118	.686	.118	1.878	2.357	18.000	33	.000
Pair 4	H_1_2 - H_1_3	-1.471	.896	.154	-1.783	-1.158	-9.574	33	.000
Pair 5	H_1_2 - H_1_4	-.471	1.080	.185	-.847	-.094	-2.541	33	.016
Pair 6	H_1_3 - H_1_4	1.000	.853	.146	.702	1.298	6.837	33	.000
Pair 7	H_2_1 - H_2_2	2.176	.716	.123	1.926	2.426	17.712	33	.000
Pair 8	H_2_1 - H_2_3	.824	1.114	.191	.435	1.212	4.311	33	.000
Pair 9	H_2_1 - H_2_4	1.676	1.319	.226	1.216	2.137	7.409	33	.000
Pair 10	H_2_2 - H_2_3	-1.353	1.041	.179	-1.716	-.990	-7.578	33	.000
Pair 11	H_2_2 - H_2_4	-.500	1.503	.258	-1.024	.024	-1.940	33	.061
Pair 12	H_2_3 - H_2_4	.853	1.540	.264	.316	1.390	3.229	33	.003
Pair 13	H_3_1 - H_3_2	2.412	.783	.134	2.139	2.685	17.959	33	.000
Pair 14	H_3_1 - H_3_3	1.147	1.019	.175	.792	1.503	6.564	33	.000
Pair 15	H_3_1 - H_3_4	.441	1.440	.247	-.061	.943	1.787	33	.083
Pair 16	H_3_2 - H_3_3	-1.265	.618	.106	-1.480	-1.049	-11.926	33	.000
Pair 17	H_3_2 - H_3_4	-1.971	1.141	.196	-2.369	-1.572	-10.069	33	.000
Pair 18	H_3_3 - H_3_4	-.706	1.219	.209	-1.131	-.280	-3.376	33	.002
Pair 19	H_4_1 - H_4_2	.794	1.067	.183	.422	1.166	4.340	33	.000
Pair 20	H_4_1 - H_4_3	-.618	1.577	.270	-1.168	-.068	-2.284	33	.029
Pair 21	H_4_1 - H_4_4	-1.235	1.689	.290	-1.825	-.646	-4.265	33	.000
Pair 22	H_4_2 - H_4_3	-1.412	1.184	.203	-1.825	-.999	-6.955	33	.000

[17] To manage the data, the conditions were coded. The letter stands for hue, saturation or brightness, the first digit is the number of the color and the second digit is the number of box that the objects are located. For instance H_2_3 corresponds to the "result of preference of *hue* for the 2nd *color* (S3060-G50Y) in the 3rd *box*" or "S_4_2 corresponds to the "result of preference of *saturation* for the *4th color* (S3060-Y50R) in the 2nd *box*.

APPENDIX F

AN EXAMPLE SURVEY LEAFLET



Bu kısmı doldurunuz

Yaş:________ Cinsiyet: K E

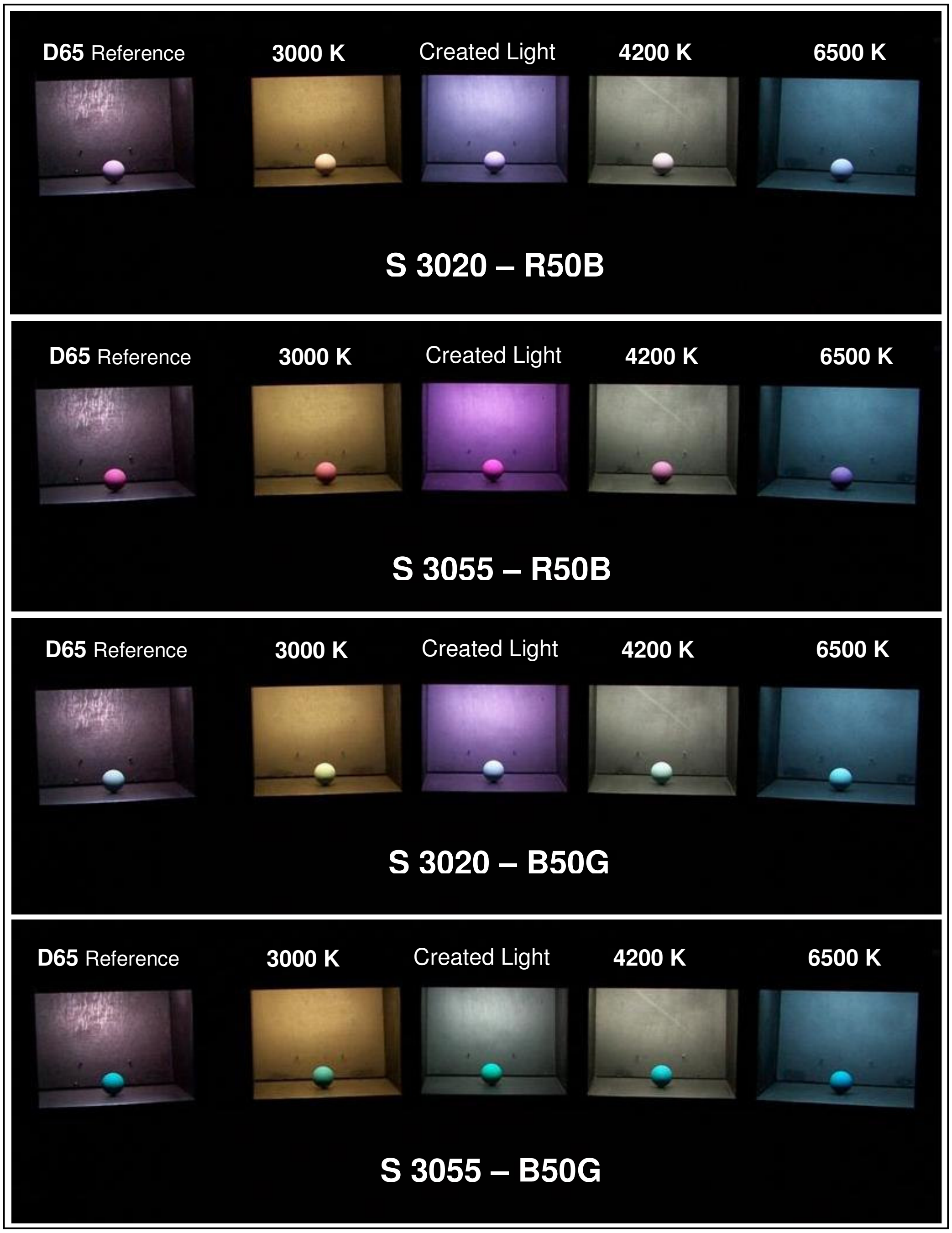
1

Renk Numarası:
S 3020 - G50Y

REFERANS

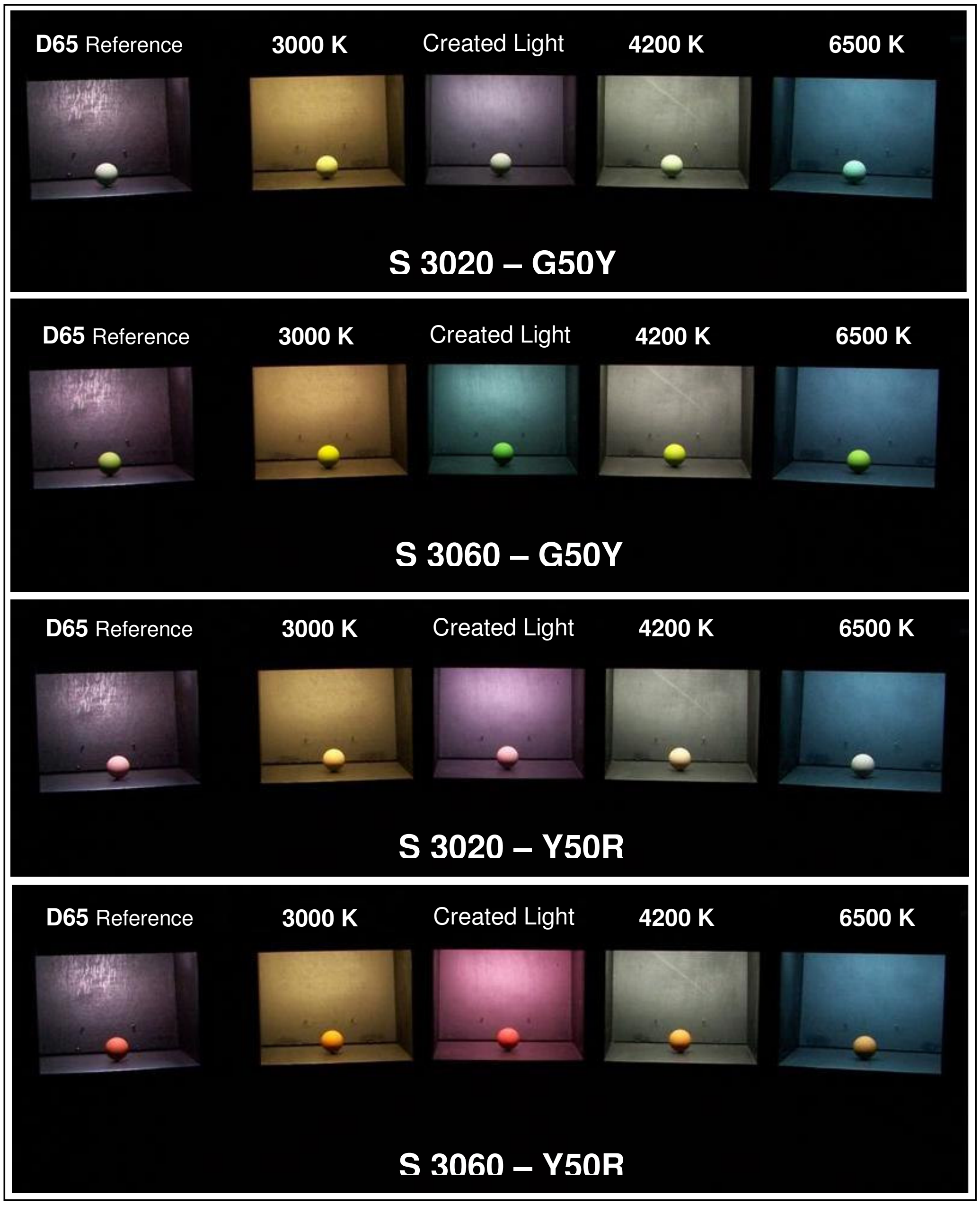
	1. KUTU	2. KUTU	3. KUTU	4. KUTU	5. KUTU
Sağdaki dört kutuyu, soldaki kutunun **RENK** yakınlığına göre sırlayınız.		1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
Sağdaki dört kutuyu, soldaki kutunun **PARLAKLIK DERECESİNE** yakınlığına göre sıralayınız.		1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
Sağdaki dört kutuyu, soldaki kutunun **CANLILIK DERECESİNE** yakınlığına göre sıralayınız.		1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4
Sağdaki dört kutuyu, soldaki kutunun **BELİRGİNLİK DERECESİNE** yakınlığına göre sıralayınız.		1 2 3 4	1 2 3 4	1 2 3 4	1 2 3 4

1: Referansa en yakın 4: Referansa en uzak


D65 Reference
3000 K
Created Light
4200 K
6500 K
S 3020 – R50B
D65 Reference
3000 K
Created Light
4200 K
6500 K
S 3055 – R50B
D65 Reference
3000 K
Created Light
4200 K
6500 K
S 3020 – B50G
D65 Reference
3000 K
Created Light
4200 K
6500 K
S 3055 – B50G

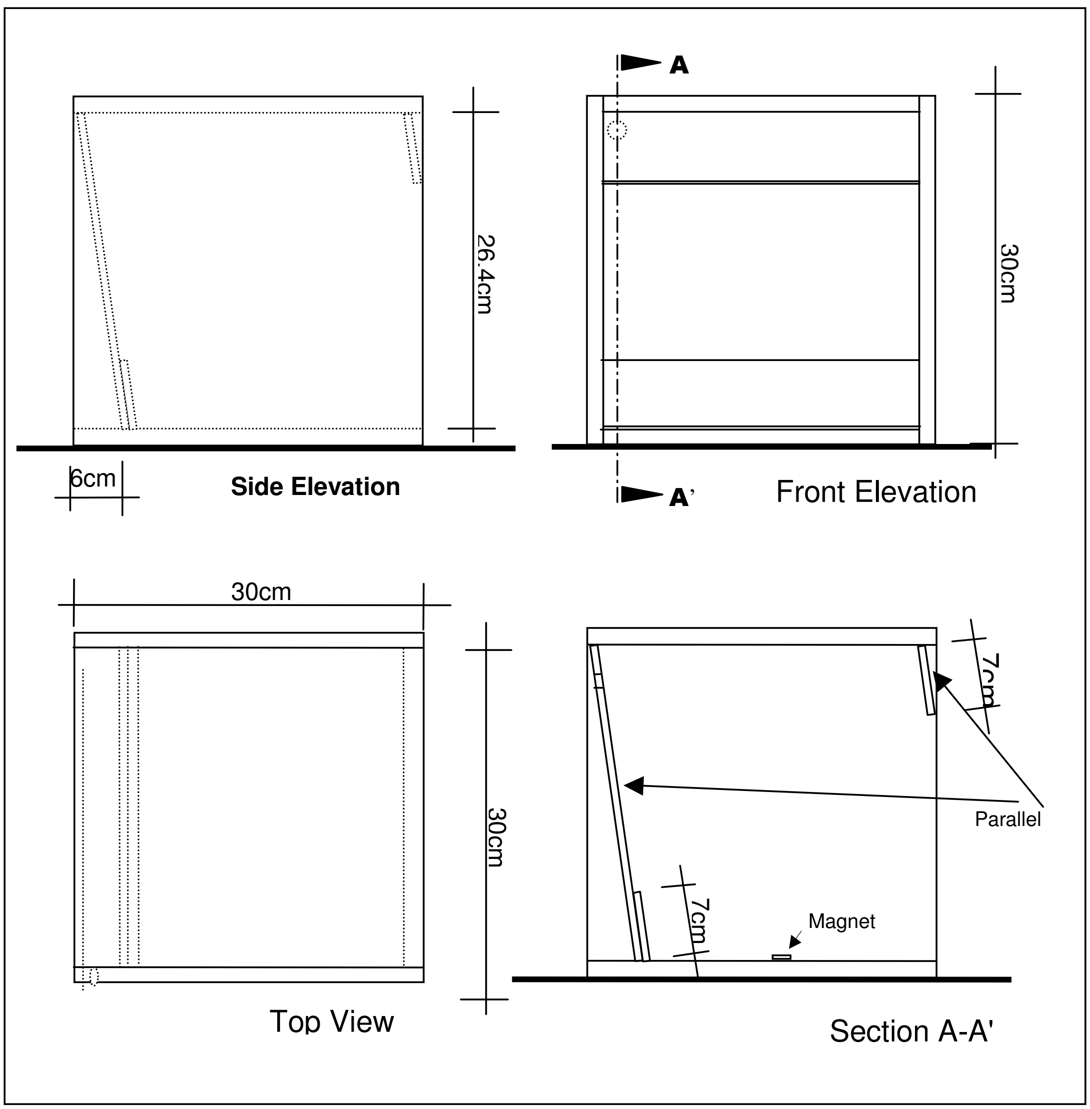
APPENDIX E

THE LIT BOXES WITH COLORED OBJECTS



APPENDIX D

TECHNICAL DRAWING OF DALI BOXES



APPENDIX C

DEFINITION OF TERMS[16]

Chromaticity Coordinates: The ratio of each of the three stimulus values to their sum. The symbols recommended for the Chromaticity Coordinates are: *x* and *y* in the CIE 1931 standard colorimetric system.

Color Temperature: Temperature of the full radiator that emits radiation of the same chromaticity as the radiation considered. The unit is Kelvin.

Correlated Color Temperature: The Color Temperature corresponding to the point on the Planckian Locus, that is nearest to the point representing the chromaticity of the illuminant considered on an agreed uniform-chromaticity-scale diagram. The unit is Kelvin.

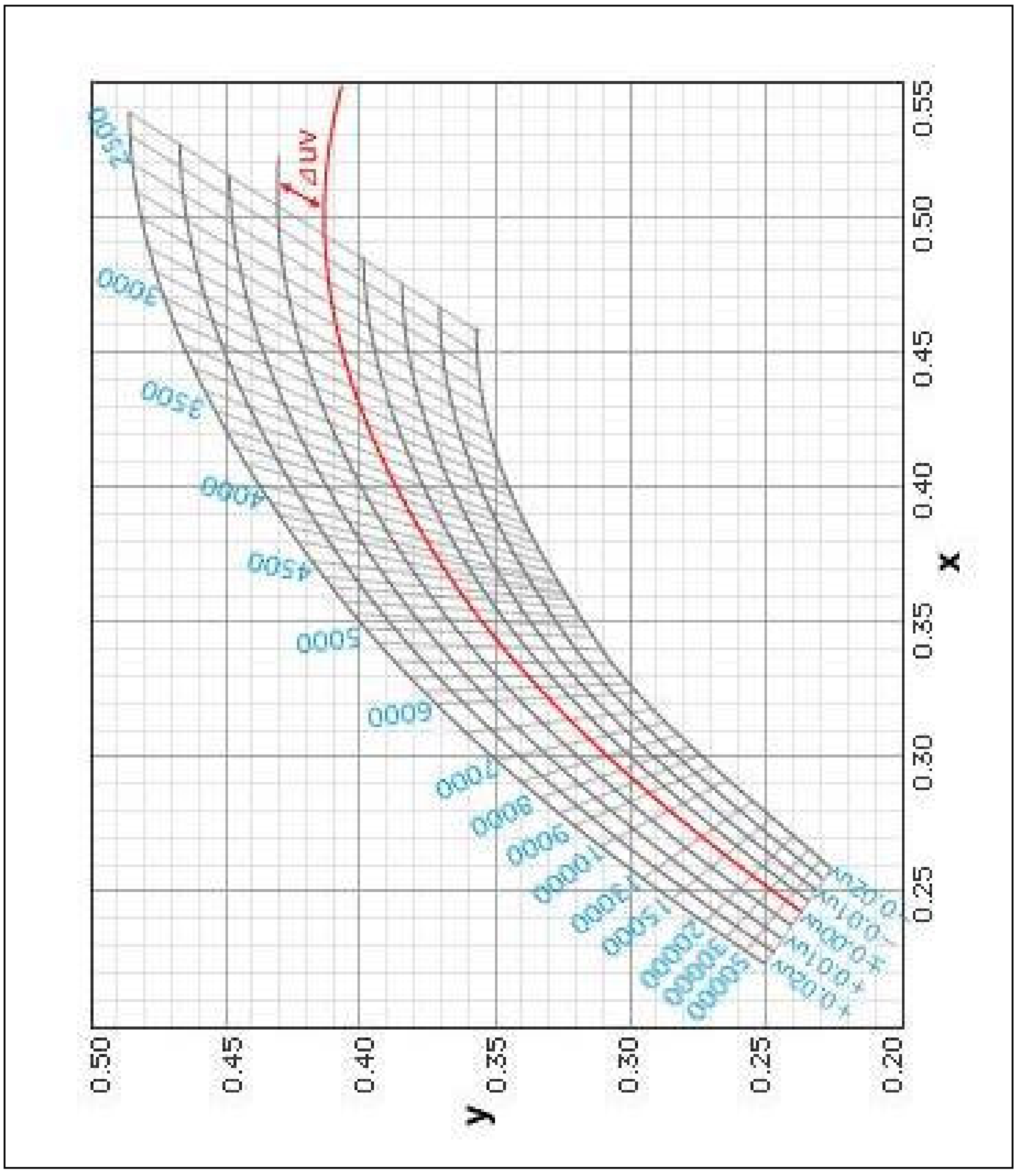
Color Rendering Index: Measure of the degree to that the perceived colors of objects illuminated by the source conforms to those of the same objects illuminated by a reference illuminant for specified conditions. The unit is Ra.

D65: D65 is a standard illuminant that represents daylight with a Correlated Color Temperature of 6504 Kelvin.

[16] The definitions of these terms are derived from the International Lighting Vocabulary, CIE 1970, 1988.

APPENDIX B

CIE 1931 CHROMATICITY DIAGRAM ISO-TEMPERATURE LINES



NCS	Natural Color System.
Nm	Nanometers.
OIC	Object Identification Card.
OIDA	Optoelectronics Industry Development Association.
Pc-LED	Phosphor-coated Light Emitting Diode.
PN Junction	Positive Negative Junction.
RGB LEDs	Red Green Blue Light Emitting Diodes.
UV	Ultraviolet Radiation.

APPENDIX A

LIST OF ABBREVIATIONS

AlGaInP	Aluminum Gallium Indium Phosphide.
CC	Chromaticity Coordinates.
CCT	Correlated Color Temperature.
CT	Color Temperature.
CIBSE	Chartered Institution of Building Services Engineers.
CIE	Commission Internationale de L'eclairage – International Commission on Illumination.
CRI	Color Rendering Index.
DALI	Digital Addressable Lighting Interface.
DALI AG	Digital Addressable Lighting Interface Activity Group.
DIN	Deutsches Institut für Normung (German Institute of Standarts).
ICOM	International Council of Museums.
IES	Illuminating Engineering Society.
IESNA	Illuminating Engineering Society of North America.
InGaN	Indium Gallium Nitride.
IR	Infrared Radiation.
LED	Light Emitting Diode.
NCPTTC	National Center for Preservation Technology and Training Committee.

Ventura, T. (n.d.). *Psychoanalysis*. Retrieved April 8, 2002, from http://allpsych.com/journal/psychoanalysis.html.

Wald, G, & Griffin, D. R. (1947). The change in refractive power of the human eye in dim and bright light. *Journal of The Optical Society of America*, *37*(5), 321-336.

Williams, B. (2005). A history of light and lighting. Retrieved November 22, 2006, from http://www.mts.net/~william5/history/hol.htm.

Wyszecki, G., &. Stiles, W. S. (1982). *Color science: Concepts and methods, quantitative data and formulae*. New York: John Wiley & Sons.

Osram: Incandescent Lamps. (n.d.). Retrieved February 28, 2005, from http://www.osram.com/service_corner/glossary/popups/17.html.

Philips Lighting. (1993). *Philips lighting manual* (5th ed.). Eindhoven: Lighting Design & Application Center.

Pridmore W. R., Huertas, R., Melgosa, M, & Negueruela, A, I. (2005). Discussion on perceived and measured wine color. *Color Research & Application, 30*(2), 146-152.

Pridmore W. R. (2006). Effects of luminance, wavelength and purity on the color attributes: Brief review with new data and perspectives. *Color Research & Application, 32*(3), 208-222.

Pridmore W. R. (2007). Effect of purity on hue (Abney Effect) in various conditions. *Color Research & Application*, *32*(1), 25-39.

Quiet revolution may change the way we light our world. (2002). Retrieved February 1, 2007,from http://www.sandia.gov/media/NewsRel/NR2002/LEDS2.htm.

Robilotto, R., & Zaidi Q. (2006). Lightness identification of patterned three-dimensional, real objects. *Journal of Vision*, *6*, 18-36.

Scuello, M., Abramov, I., Gordon, J., & Weintraub, S. (2003). Museum lighting: Why are some illuminants preferred. *Optical Society of America Journal*, *21*(2), 306-11.

Scuello, M., Abramov, I., Gordon, J., & Weintraub, S. (2004). Museum lighting: Optimizing the illuminant. *Color Research & Application*, *29*(2), 121-27.

Spagnoli, F. (2002). *Color Kinetics Demonstrates Led-Based Intelligent White Light Prototypes at Lightfair 2002*. Retrieved January 31, 2007, from http://www.colorkinetics.com/corp/news/pr/archive/whitelight_proto.htm?q=printme.

Steigerwald, D. A., Bhat, J. C., Collins, D., Fletcher, R. M. Holcomb, M. O., Ludowise, M. J., et al. (2002). Illumination with solid-state lighting technology. *IEEE Journals on Selected Topics in Quantum Electronics*, *8*(2), 310-320.

Stevens, J. C., & Stevens, S. S. (1963). Brightness function: Effects of adaptation. *Journal of The Optical Society of America, 53*(3), 375-385.

The NCS System. (2002). Retrieved March 6, 2007 from http://83.168.206.163/webbizz/mainPage/main.asp.

Thornton, W. A. (1992). Towards a more accurate and extensible colorimetry. *Color Research & Application*, *17*, 79-122.

IES. (1984). *IES lighting handbook: Reference Volume.* New York: Illuminating Engineering Society of North America.

IES. (1987). *IES lighting handbook: Application volume*. New York: Illuminating Engineering Society of North America.

IES. (1996). *IES museum and art gallery lighting: A recommended practice*. New York: Illuminating Engineering Society of North America.

IESNA. (2000). *IESNA lighting handbook: Reference and application*. New York: Illuminating Engineering Society of North America.

Johnson, G. M., & Fairchild M. D. (2005). *CRC: Chapter on visual psychophysics and color appearance*. Retrieved July 23, 2007, from page 3 at www.cis.rit.edu/fairchild/PDFs/PAP13.pdf.

Kaiser, P. K. (1996). Chromaticity diagram. Retrieved 15 January, 2006, from http://www.yorku.ca/eye/thejoy.htm.

Kerr, D. A. (n.d.). *Color temperature*. Retrieved November 11, 2006, from http://doug.kerr.home.att.net/pumpkin/Color_Temperature.pdf.

Kesner, C. W. (1993). Museum exhibition lighting: Visitor needs and perceptions of quality. *Journal of Illuminating Engineering Society*, *1*, 45-55.

Kruithof, A. A. (1941). Luminescence Lamps for General Illumination. *Philips Technical Review*, *6*, 65-69.

Lighting Research Center. (1998). *Museum lighting protocol project: Archeology and collections series.* New York: National Center for Preservation Technology and Training.

Melgosa, M., Rivas, M. J., Hita, E., & Vienot, F. (2000). Are we able to distinguish color attributes? *Color Research & Application*, *25*(5), 356-367.

Muthu, S., Schuurmans, F. J. P., & Pashley, M.D. (2002). Red, Green and Blue LEDs for White Light Illumination. *IEEE Journals on Selected Topics in Quantum Electronics*, *8*(2), 333-338.

Narukawa, Yukio, & Mukai, T. (2003). High Color Rendering and High Luminous Efficacy White Light Emitting Diodes. *Conference on Lasers & Electro-optics CLEO-03*, 346-47.

Nayatani, Y. (2000). On attributes of achromatic and chromatic object-color perceptions. *Color Research & Application*, *25*(5), 318-332.

NCPTT. (1999). *Museum Lighting Protocol.* Washington: NCPTT, Department of the Interior, National Park Service.

Cree launches new XLamp®: XR-C Power LEDs. (n.d.). Retrieved February 24, 2006, from http://www.cree.com/products/xlamp_new_xrc.asp.

DALI-AG of ZVEL Division Luminaries. (2005). *DALI: Digital addressable lighting interface.* Retrieved March 11, 2007, from http://www.dali-ag.org/c/manual_gb.pdf.

Davis, R.G., & Ginthner, D. N. (1993). Correlated color temperature, illumination level and the Kruithof curve. *Journal of Illuminating Engineering Society*, *22*, 45-45.

Dean, D. (1994). *Museum exhibition: Theory and practice*. London: Routledge.

Dikel, E., & Yener, C. (2007). A lighting coordinate database for three dimensional art objects. *Building &Environment*, *42*(1), 246-53.

Druzik, J. (2004). Illuminating Alternatives. *GCI Newsletters*, *19*(1). Retrieved April 12, 2005, from www.getty.edu/conservaiton/publications/newsletters/19_1/news in cons1.html.

Egan, D. M., & Olgyay, V. W. (2002). *Architectural lighting*. New York: McGraw Hill.

Ewald Hering. (n.d.). Retrieved July 12, 2007, from http://www.colorsystem.com/projekte/engl/24here.htm.

Garson, G. D. (n.d.). Scales and standard measures: Key concepts and terms. Retrieved September 4, 2007, from http://www2.chass.ncsu.edu/garson/PA765/standard.htm

Gee, J. (2002). *Sandia joins revolution in solid-state lighting: Quiet revolution may change way we light our world*. Retrieved January 31, 2007, from http://www.sciencedaily.com/releases/2002/04/020417070346.htm.

Haitz, R., Kish F., Tsao, J, & Nelson, J. (1999). The case for a national research program on semiconductor lighting. *Proceedings of the Optoelectronics Industry Development Association Forum*, New York, 2-8 October 1999, pp. 348-358. Washington, DC: OIDA.

Hunt, R. W. G. (1952). Light and Dark Adaptation and the Perception of Color. *Journal of The Optical Society of America, 42*(3), 190-199.

ICOM. (1953). *Use of fluorescent light in museums: General remarks and practical advice for museum directors and curators*. Paris: Commission for Lighting of Museum Objects-ICOM International Committee on Museum Techniques.

REFERENCES

About SPSS Inc. (n.d.). Retrieved September 4, 2007, from http://www.spss.com/corpinfo/spss_edge.htm

A Solid Future for Lighting. (2001) Retrieved October 9, 2002, from http://www.economist.com/science/displayStory.cfm?story_id=136510

Anstis, S. (2002). The Purkinje rod-cone shift as a function of luminance and retinal eccentricity. *Vision Research*, *42*, 2485-2491.

Bierman, A. (1998). LEDs: From indication to illumination? Lighting Futures 3.4. Retrieved March 1, 2005, from http://www.lrc.rpi.edu/programs/Futures/LF-LEDs/index.asp>.

Borbely, A., Samson, A., & Schanda, J. (2001). The concept of correlated color temperature revisited. *Color Research & Application*, *26*, 450-57.

Boyce, P. R. (1987). Visual acuity, color discrimination, and light level. *Lighting: A Conference on Lighting in Museums, Galleries, and Historic Houses* (pp. 45-67). London: The Museum Association of United Kingdom.

BSI. (n.d.). *BSI BS 950 PART 1 Artificial daylight for the assessment of color Part 1: Illuminant for color matching and color appraisal*. Retrieved 12 February 2006, from http://engineers.ihs.com/document/abstract/AJFTCAAAAAAAAAAA.

Bullough, J. D. (2003). Lighting answers: LED lighting systems. *NLPIP Lighting Answers*, *7*(3), 1-23.

CIE. (1970). *CIE publication No. 17.E-1.1: International lighting vocabulary*. Paris: Commission Internationale de l'Eclerage.

CIE. (1988). *CIE publication No. 17.4: International lighting vocabulary*. Vienna: Central Bureau of Commission Internationale de l'Eclerage.

Çığırgan, E. (1995). Lighting in museums. *Preservation & Restoration*, *1*, 1-15.

Anybody working with museums should always keep in mind that the role of a museum is to collect, preserve, analyze and display artifacts and examples of human achievement and their impact on us. Light is the most powerful tool to reveal this impact.

viewing points. The ideally oriented lighting should reinforce the appearance of its details. CC of the light source would be essential for these delicate applications.

Since this study proposed a new method in museum lighting, and a "primary milieu of a museum is the 'real thing', it may be assumed that all that is required is to place objects on public view and let them speak for themselves" (Dean, 1994, p. 5). Other institutions also deal with information, but only museums uniquely collect, preserve, research, and publicly display objects as an essential function of their existence. By using the method proposed in this dissertation, lighting designers and curators of each museum will have a tool for creating the best lighting conditions of objects.

Although the dissertation was concentrated on museum lighting, it can be used as guidance in any kind of display application, where the primary aim is to reinforce the visual properties of the object and to draw the attention to the product. For example, a shop window, a display cabinet, even an important souvenir at home can apply this method. In the further studies, experiments similar to the one in this study can be conducted with more complex objects rather than a sphere. The objects can also be a group of objects combined in a certain composition. The light sources can be located as key, fill and backlights, so that the three dimensional appearance of the objects under the created light can be tested. The effect of created light on the figure-background relations can also be investigated. On the other hand, some special textures and other surface properties of the objects can be tested.

significant objects of their collections and illuminate the remaining ones by time, as their budget allow.

Every object of the collection of a museum has an “Object Identification Card”. This card provides information about the object and its properties: its name, identification number, country or origin, material, date, artist or maker, description, and dimensions. In addition to this essential data, the type and exposure duration of the light sources, and their location[15] can be added. The issue of “type of the light sources” should be elaborated with the Chromaticity Coordinates values. Thus a change of the location of the object in the museum, or an object transfers to another museum for a temporary exhibition, will allow the CC of the light source to be selected accordingly. Although exhibition conditions, the design of the exhibition cabinets, illuminance levels at the surroundings or the overall theme of the exhibition all effects the perception of the object, the inclusion of CC values would provide lighting designers the most suitable light source.

In this digital age, a new term “the virtual museum” penetrated all literature. It is advantageous for both viewers and objects. Viewers can access the collections of the virtual museums by using their network-connected computers, anywhere in the world, and unique objects may be exhibited without any risk or damages to the objects. In a virtual museum, the lighting of objects would be different. In digital exhibitions, the visitors virtually walk around an object and experience the effect of light and shadow from different

[15] The method for providing the location of the light sources, and their formulation methodology were studied earlier (Dikel & Yener, 2007, p. 247).

museum lighting will be based on a scientific basis, no longer on intuition alone.

Light source decision, in the current museum lighting practice, is made from a couple of possible conventional alternatives in the market such as metal halide, fluorescent or halogen, from several manufacturers. Although they fulfill the upper and lower limits of general quantitative data in the guidelines of institutions, they are not energy-efficient light sources. With low energy consumption properties and many other advantages, LEDs are penetrating the lighting industry rapidly, and in the very near future, most lighting designers in museums will become more familiar with LEDs. Thus the usage of LEDs in museum lighting will become common practice for the curators and lighting designers.

Light obtained with the LED clusters, specially created in the laboratory of the museum, can easily become a part of the lighting scheme. As indicated earlier, the creation technique of the light source described in this dissertation is at its early stages. However, in the future, the manual adjustment method of RGB LED clusters will be replaced by more sophisticated techniques that will increase the performance and decrease the time required to create the desired light.

It is not an obligation to illuminate all objects by using this method, since the cost of light measurement devices and working hours can be expensive for museums with a relatively low budget. They can start to illuminate the most

7. CONCLUSION

The dissertation was aimed to create a new tool for lighting designers or curators working in museums. By using this new tool, objects can be illuminated uniquely by referring to their surface color. There are immense types of museum objects, and it is nearly impossible to create guidelines for illuminating each one of them.

The current lighting methods are generally based on intuitions and rules of thumb such as illuminating gold-like metals with low CCT light sources and silver-like ones with high CCT sources. In general, light source decisions are based on these general assumptions and the personal experience of the lighting designer. Illuminating museum objects requires delicate decisions by designers who are experienced and talented in their field. It is rare to find such qualified people in every museum, even if they were found, it is difficult for them to obtain necessary equipment and to spend great amount of time for a successful lighting scheme for each object. Although a talented and experienced curator and a skillful lighting designer can achieve good results in display lighting, illumination of museum objects should not be left solely to intuition, experience, and personal talent. So with spending less time and energy of the staff, this method can be used in museums to create a lighting scheme based on a technically reliable basis. With the help of this method, experiment, for the colors that have yellow, the preference of the saturation shifted to the tints. For the colors that have blue, the result was the opposite.

Although certain relations between the pairs of colors can be observed, subjects preferred the appearance of the brightness of the objects under the created light. Created lights that had the same CC values as the objects rendered the saturation of the colors better than the other conventional light sources.

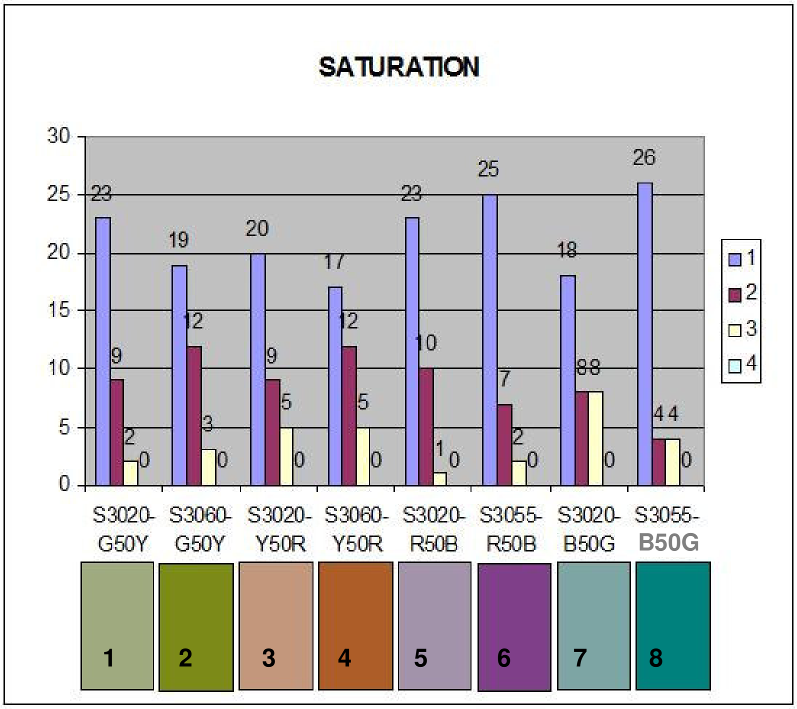


Figure 6.3. The Graph of Preference of Saturation for the Selected Colors, illuminated by the Created Light.

The saturated colors S3060-G50Y (color 2) and S3060-Y50R (color 4) were not preferred more than their tints. Since the tints of the colors were preferred that the shades, for the first two color pairs, Hunt effect (see Chapter 3.3.3.) can be observed. On the other hand, in the last two pairs, the more saturated colors S3055-R50B (color six) and S3055-R50B (color eight) were preferred when compared to their tints.

When compared the more saturated colors, S3060-G50Y (color two), S3060-Y50R (color four), S3055-R50B (color six), and S3055-B50G (color eight), yellow (in color two and four) and blue (in color six and eight) colors are common. Despite the fact that it is difficult to make a generalization in the

A t-test was conducted for the pairs of conditions. Similar to hue and brightness, the significance of the pairs including the second box was examined. All the pairs have significances below 0.05, except the 41st pair (Appendix G.3). In that pair, saturation of the seventh color, S3020-B50G, was evaluated under the conditions in the second box and the fourth box. The significance 0.451 reveals the fact that subjects had difficulty in evaluating the created light and the LED with 6500-Kelvin CCT. The color, S3020-B50G, is a blue dominant, turquoise-like color. The reason for the confusion of the subjects could be the blue-dominant spectral characteristics of the 6500-Kelvin LED in the fourth box.

Valuable data were gathered after the evaluation of the saturation of the colors under four lights results. Similar to the results of brightness, the first two color pairs, S3020-G50Y – S3060-G50Y and S3020-Y50R – S3060-Y50R, have significant differences than the last two color pairs, S3020-R50B – S3055-R50B and S3020-B50G – S3055-B50G. For the first two pairs, the preferences of the tints of the colors were more than their shades. The opposite result was obtained for the last two pairs (Figure 6.3)

Table 5.23. Saturation Frequency for Color: S3055-R50B, Light: Created Light

S_6_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	25	73.5	73.5	73.5
	2	7	20.6	20.6	94.1
	3	2	5.9	5.9	100.0
	Total	34	100.0	100.0	

In the seventh condition, 18 subjects (52.9%) preferred the created light (Table 5.24) while light in the final condition was preferred by 26 subjects (76.5%) (Table 5.25).

Table 5.24. Saturation Frequency for Color: S3020-B50G, Light: Created Light

S_7_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	18	52.9	52.9	52.9
	2	8	23.5	23.5	76.5
	3	8	23.5	23.5	100.0
	Total	34	100.0	100.0	

Table 5.25. Saturation Frequency for Color: S3055-B50G, Light: Created Light

S_8_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	26	76.5	76.5	76.5
	2	4	11.8	11.8	88.2
	3	4	11.8	11.8	100.0
	Total	34	100.0	100.0	

In all conditions, subjects continuously preferred the created light that reveals the saturation of the colors successfully.

In the fourth condition, the saturation of S3060-Y50R was evaluated. 17 subjects (50%) preferred the created light, while 12 (35.3%) ranked it two and 5 subjects (14.7%) ranked it three (Table 5.21).

Table 5.21. Saturation Frequency for Color: S3060-Y50R, Light: Created Light

S_4_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	17	50.0	50.0	50.0
	2	12	35.3	35.3	85.3
	3	5	14.7	14.7	100.0
	Total	34	100.0	100.0	

The fifth condition showed a significant preference of the created light. 23 subjects (67.6%) prefers that light and it was the second choice of only 10 subject (29.4%) (Table 5.22).

Table 5.22. Saturation Frequency for Color: S3020-R50B, Light: Created Light

S_5_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	23	67.6	67.6	67.6
	2	10	29.4	29.4	97.1
	3	1	2.9	2.9	100.0
	Total	34	100.0	100.0	

The saturation of the sixth color, S3055-R50B, was revealed successfully under the created light to 25 subjects (73.5%) (Table 5.23).

Table 5.18. Saturation Frequency for Color: S3020-G50Y, Light: Created Light

S_1_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	23	67.6	67.6	67.6
	2	9	26.5	26.5	94.1
	3	2	5.9	5.9	100.0
	Total	34	100.0	100.0	

The brightness of the second color was evaluated and 19 subjects (55.9%) preferred the created light, whereas 12 subjects (35.3%) gave a rank of two (Table 5.19).

Table 5.19. Saturation Frequency for Color: S3060-G50Y, Light: Created Light

S_2_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	19	55.9	55.9	55.9
	2	12	35.3	35.3	91.2
	3	3	8.8	8.8	100.0
	Total	34	100.0	100.0	

The performance of the created light on the brightness of the third color, S3020-Y50R, was the first choice of 20 subjects (58.8%). Nine and five subjects (26.5% and 14.7%) gave a rank of two and three, respectively (Table 5.20).

Table 5.20. Saturation Frequency for Color: S3020-Y50R, Light: Created Light

S_3_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	20	58.8	58.8	58.8
	2	9	26.5	26.5	85.3
	3	5	14.7	14.7	100.0
	Total	34	100.0	100.0	

to the shades. However, the preference ranking data showed no certain relation between the tints and shades of any colors.

The first and fifth colors were preferred less than their shades, second and sixth colors. On the contrary, the third color was preferred more than its shade. For the case of colors S3020-B50G and S3055-B50G, the evaluations were equal. The preference rank of the fourth color, S3060-Y50R, had an outstanding result. The number of subjects, who ranked it one and two were same. This can be explained by the luminance of this color that is relatively low, when compared to other colors.

Although a certain relation cannot be observed in the data distribution, the brightness of the eight colors was preferred when compared to other light sources.

5.4. ANALYSIS OF PREFERENCE OF SATURATION

The subjects evaluated the appearances of the saturation of the eight colors. The results were statistically analyzed and frequency tables for each color with the created light was prepared. In the first condition, 23 subjects (67.6%) gave a rank of one, whereas 9 subjects (26.5%) gave a two and 2 subjects (5.9%) ranked it three (Table 5.18).

no certain relation between the tints and shades of the color pairs. However, the first four colors and the last four colors showed an unusual distribution of scores (Figure 6.2).

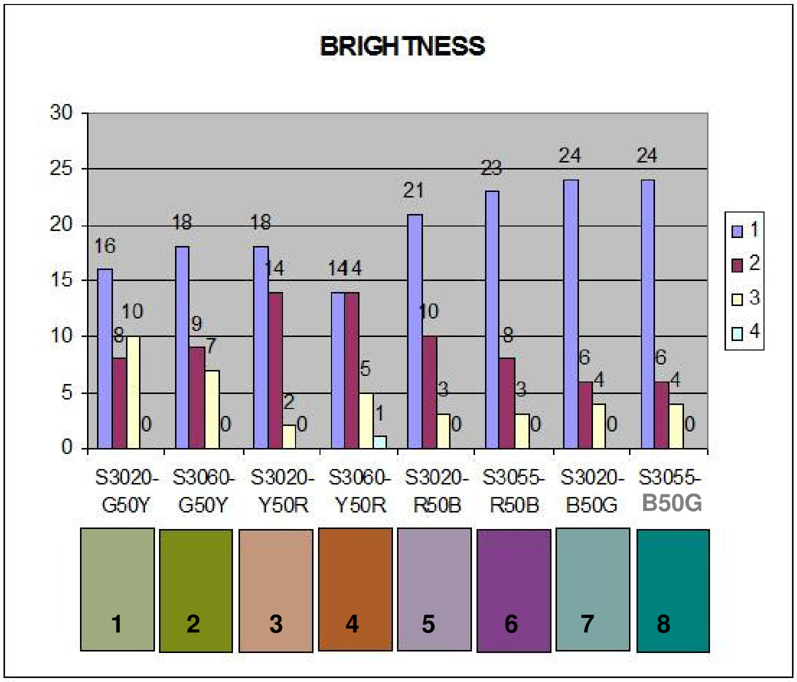


Figure 6.2. The Graph of Preference of Brightness for the Selected Colors, illuminated by the Created Light.

The distribution of the preference levels in the first four colors was below 20 subjects (58.8%). On the last four colors, it was the opposite. The subjects found the final four colors as the best light source, where as for the first four colors, they could not evaluate the colors clearly. Especially for the third and fourth colors, the ranks one and two were very similar.

In the data, gathered for the evaluation of brightness, Helmholtz-Kohlrausch effect would be expected to appear. This effect, explained in Chapter 3.3.2, hypothesized that; the tints of all colors should be preferred when compared

Table 5.17. Brightness Frequency for Color: S3055-B50G, Light: Created Light

B_8_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	24	70.6	70.6	70.6
	2	6	17.6	17.6	88.2
	3	4	11.8	11.8	100.0
	Total	34	100.0	100.0	

Except for the third and fourth conditions, the majority of the subjects found the created light to be the ideal light source that reveals the brightness of the colors successfully.

A t-test was conducted between the 48 pairs, to display the two-tailed probability of the difference. All the pairs, including the second box, have certain significances. Only the fifth and eleventh pairs showed significances of 0.615 and 0.065, respectively, that is, greater than 0.05 (Appendix G.2). In the case of the fifth pair, the object with S3020-G50Y color in the second box was compared with the same color in the fourth box. In the eleventh pair, the second box and the fourth box were compared to the color S3060-G50Y. The first color, S3020-G50Y, with the significance of 0.615, is the tint of the second color having a significance of 0.065. The colossal significance, difference between these two pairs, is due to the brightness levels of the two colors.

The subjects evaluated the brightness of the color of the objects under the created light. The data gathered from their evaluation showed that the subjects preferred the created light. Unlike the evaluation of hue, there was

The sixth condition showed a significant preference of the created light. 23 subjects (67.6%) ranked it one, whereas 8 and 3 ((23.5% and 8.8%) subjects ranked it two and three, respectively (Table 5.15).

Table 5.15. Brightness Frequency for Color: S3055-R50B, Light: Created Light

B_6_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	23	67.6	67.6	67.6
	2	8	23.5	23.5	91.2
	3	3	8.8	8.8	100.0
	Total	34	100.0	100.0	

In the seventh condition, 24 subjects (70.6%) found created light to be the ideal light source for the appearance of brightness of the object, painted with S3020-B50G (Table 5.16).

Table 5.16. Brightness Frequency for Color: S3020-B50G, Light: Created Light

B_7_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	24	70.6	70.6	70.6
	2	6	17.6	17.6	88.2
	3	4	11.8	11.8	100.0
	Total	34	100.0	100.0	

In the final condition, the same result was obtained, 24 subjects (70.6%) preferred the created light (Table 5.17).

In the fourth condition, a similar result was obtained. The number of subjects (14 – 41.2%), who ranked it one, is the same as those, who ranked it two (Table 5.13).

Table 5.13. Brightness Frequency for Color: S3060-Y50R, Light: Created Light

B_4_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	14	41.2	41.2	41.2
	2	14	41.2	41.2	82.4
	3	5	14.7	14.7	97.1
	4	1	2.9	2.9	100.0
	Total	34	100.0	100.0	

The reason for these insignificant results may be the nature of the colors: S3020-Y50R and S3060-Y50R. These colors have red on the color composition of their surface. The subjects evaluated the colors under four lights, in comparison to the D65 illuminant that has dominant blue wavelength in its spectral distribution. It is clear that the appearance of a color with red pigments, under the reddish created light (with low CCT), will not appear same as it would under the bluish reference illuminant (with high CCT).

In the fifth condition, 21 subjects (61.8%) preferred the performance of the created light on the appearance of the brightness of the fifth color (Table 5.14).

Table 5.14. Brightness Frequency for Color: S3020-R50B, Light: Created Light

B_5_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	21	61.8	61.8	61.8
	2	10	29.4	29.4	91.2
	3	3	8.8	8.8	100.0
	Total	34	100.0	100.0	

In the second condition, in which the subjects were evaluating the brightness of the object, painted with the second color (S3060-G50Y), 18 subjects (52.9%) found the created light to be the best light source (Table 5.11)

Table 5.11. Brightness Frequency for Color: S3060-G50Y, Light: Created Light

B_2_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	18	52.9	52.9	52.9
	2	9	26.5	26.5	79.4
	3	7	20.6	20.6	100.0
	Total	34	100.0	100.0	

Different from the other conditions, mentioned above, the third condition showed only a minor significance between the preference levels of the subjects. In this condition, 18 subjects (52.9%) gave a rank of one, whereas 14 subjects (41.2%) gave a rank of two. Although the number of subjects, whose first choice was the created light, is greater than those who put the created light into second position, the majority of the subjects preferred the created light (Table 5.12).

Table 5.12. Brightness Frequency for Color: S3020-Y50R, Light: Created Light

B_3_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	18	52.9	52.9	52.9
	2	14	41.2	41.2	94.1
	3	2	5.9	5.9	100.0
	Total	34	100.0	100.0	

like the others, were evaluated under D65 illuminant for reference. This illuminant, with its blue-dominant spectral distribution characteristics, rendered the colors S3020-R50B and S3055-R50B different than the other pairs. The opposite of the Abney effect occurred for this case due to this fact.

For all the cases, 20 subjects (58.8%) that is more than half of the sample group, ranked the created light as the first choice. This showed that, the hue of the colors appeared more attractive for the observers, when illuminated with the light that had the same CC with the object.

5.3. ANALYSIS OF PREFERENCE OF BRIGHTNESS

The responses of the subjects for the preference of the brightness of colors under the four lights were examined. In the first condition, 16 subjects (47.1%) preferred the created light, while 8 subjects (23.5%) gave a rank of two and 10 subjects (29.4%) gave a rank of three, for the appearance of the first color under the created light (Table 5.10).

Table 5.10. Brightness Frequency for Color: S3020-G50Y, Light: Created Light

B_1_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	16	47.1	47.1	47.1
	2	8	23.5	23.5	70.6
	3	10	29.4	29.4	100.0
	Total	34	100.0	100.0	

The data gathered in this dissertation showed that the hues of the objects were preferred more, when illuminated with the created light, compared to other conventional lights. In Figure 5.1, the graphical presentation of the data shows the preference distribution of the subjects for the colors.

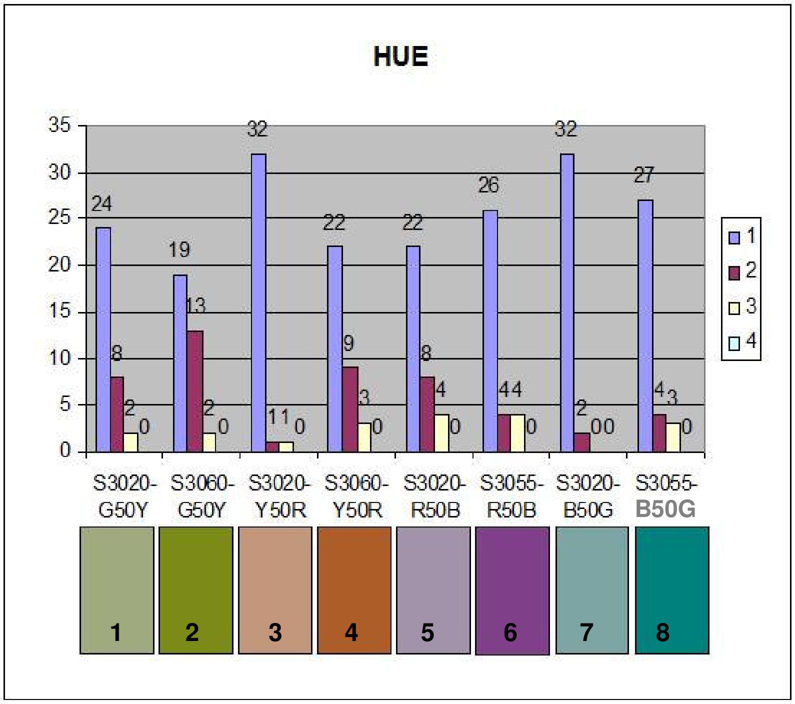


Figure 5.1. The Graph of Preference of Hue for the Selected Colors, illuminated by the Created Light.

There is a visible relation between the tint and shade tones of the color pairs. For the six colors, except the fifth and sixth colors, the tints of the colors are preferred more than their shades. This can be explained by the Abney effect, explained in Chapter 3.3.1. When white is added to the color, a shift in hue occurs and when comparing the two pairs, the tint of a color is preferred more than its shade. In the case of the color pairs, S3020-R50B and S3055-R50B, shades were preferred more than their tints. This can be explained by the blue-dominant spectral composition of the color itself. These color pairs, In all eight cases, none of the subjects found the appearance of the hue under the created light to be poor and gave a rank of four and for those eight specific conditions. The majority of the observers preferred the appearance of the hue of the objects under the created light.

The individual evaluations for the eight colors identified the preference of the subjects for each condition. However, the conditions were matched as pairs and a t-test was conducted between those 48 pairs, to display the two-tailed probability of the difference between the means (Appendix G.1). The t-test calculates whether the means of two groups are statistically different from each other.

The evaluation results of the pairs are statistically significant, if the significance is below 0.05. If the value is greater than 0.05, then there is not enough evidence to state a difference. Although the paired sample tests for hue showed 48 significance values, the pairs including the second box[14] were more valuable for the study. Among those 24 pairs, including the second box, only two of them (Pair 11 – 0.061 and Pair 29 – 0.148) showed a significance value that is greater than 0.05 (Appendix G.1, Table G.1), in the boxes with the created light and the LED sources with a CCT of 6500 Kelvin, for the colors S3060-G50Y and S3020-R50B. The reason for not having a significant difference between the appearances of the hue of the colors under these two lights may be the difficulty of differentiating the appearance of the colors between the created light and 6500 K light for these special cases.

[14] Here the second box is the box with the created light.

26 subjects (76.5%) preferred the created light in the sixth condition, while four subjects (11.85%) only as the second rank (Table 5.7).

Table 5.7. Hue Frequency for Color: S3055-R50B, Light: Created Light

H_6_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	26	76.5	76.5	76.5
	2	4	11.8	11.8	88.2
	3	4	11.8	11.8	100.0
	Total	34	100.0	100.0	

In the seventh condition, a remarkable result was obtained. 32 subjects (94.1%) preferred the appearance of the hue of S3020-B50G under the created light. Only two subjects (5.9%) gave a rank of two (Table 5.8).

Table 5.8. Hue Frequency for Color: S3020-B50G, Light: Created Light

H_7_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	32	94.1	94.1	94.1
	2	2	5.9	5.9	100.0
	Total	34	100.0	100.0	

The preference ratio of the created light in the last condition was not different from the others. 27 subjects (79.4%) gave a rank of one for the created light (Table 5.9).

Table 5.9. Hue Frequency for Color: S3055-B50G, Light: Created Light

H_8_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	27	79.4	79.4	79.4
	2	4	11.8	11.8	91.2
	3	3	8.8	8.8	100.0
	Total	34	100.0	100.0	

Table 5.4. Hue Frequency for Color: S3020-Y50R, Light: Created Light

H_3_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	32	94.1	94.1	94.1
	2	1	2.9	2.9	97.1
	3	1	2.9	2.9	100.0
	Total	34	100.0	100.0	

The fourth condition, for the object painted with S3060-Y50R, 22 subjects (64.7%) preferred the appearance under the created light, while nine subjects (26.5%) gave a rank of two, and three subjects (8.8%) gave a rank of three (Table 5.5).

Table 5.5. Hue Frequency for Color: S3060-Y50R, Light: Created Light

H_4_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	22	64.7	64.7	64.7
	2	9	26.5	26.5	91.2
	3	3	8.8	8.8	100.0
	Total	34	100.0	100.0	

For the evaluation of the fifth condition, 22 subjects (64.7%) chose the created light as the best light source among the other three light sources in the case of appearance of the hue (Table 5.6).

Table 5.6. Hue Frequency for Color: S3020-R50B, Light: Created Light

H_5_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	22	64.7	64.7	64.7
	2	8	23.5	23.5	88.2
	3	4	11.8	11.8	100.0
	Total	34	100.0	100.0	

created light. Eight subjects (23.5%) gave a rank of two and two subjects (5.9%) gave a rank of three (Table 5.2).

Table 5.2. Hue Frequency for Color: S3020-G50Y, Light: Created Light

H_1_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	24	70.6	70.6	70.6
	2	8	23.5	23.5	94.1
	3	2	5.9	5.9	100.0
	Total	34	100.0	100.0	

In the second condition, for the object with S3060-G50Y paint, 19 subjects (55.9%) preferred the created light, 13 subjects (38.2%) rated the revealing of the appearance of hue under the created light into the second place, whereas only two subjects (5.9%) recorded a rank of three (Table 5.3).

Table 5.3. Hue Frequency for Color: S3060-G50Y, Light: Created Light

H_2_2

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1	19	55.9	55.9	55.9
	2	13	38.2	38.2	94.1
	3	2	5.9	5.9	100.0
	Total	34	100.0	100.0	

The third condition showed a remarkable preference difference among the subjects. 32 subjects (94.1%) preferred the appearance of the objects under the created light (Table 5.4).

their responses. A Cronbach's Alpha value of 0.969 was obtained from the test group, after excluding five subjects (Table 5.1.).

Table 5.1. Relaibility Statistics Results

Cronbach's Alpha	N of Items
,969	34

The widely accepted cut-off for Cronbach's alpha in social sciences "should be 0.80 or higher for a set of items to be considered to have an observer accuracy" (Garson, n.d., sect. Cronbach's Alpha, para. 4). The responses of the remaining 34 "statistically reliable" subjects were investigated for the dissertation.

5.2. ANALYSIS OF PREFERENCE OF HUE

The responses of the subjects, for the eight colors under the illuminance of four different lights, were statistically analyzed. For each condition, a frequency table was prepared. Although all the data is valuable for the study to a certain degree, the conditions for the created light, however, was more important than the other conditions with 3000, 4200 and 6500 K light sources. Eight tables among 32 tables were chosen with this concern to evaluate the response of the observers.

In the first condition, 24 of 34 subjects (70.6% of the subject group) preferred the appearance of the hue of the object with S3020-G50Y paint, under the

5. DATA ANALYSIS OF THE EXPERIMENTAL STUDY

The results of the experiment were transferred into a computer as data sets. These sets were statistically investigated by using the SPSS software, Version 14. SPSS is the abbreviation of “Statistical Package for the Social Sciences” and it is widely used by more than 90% of the universities in the United States (About SPSS, n.d.).

5.1. ANALYSIS OF THE RELIABILITY OF THE SUBJECTS

Reliability is the correlation of an item, scale, or instrument with a hypothetical one that truly measures what it is supposed to (Garson, n.d.). When the true instrument is not available, reliability can be estimated by certain methods. One of the most common is the “inter-rater reliability test”. It is based on the correlation of scores between two or more raters who rate the same item, scale or instrument. “Cronbach’s alpha” or the “reliability coefficient” is the most common form of reliability coefficient for the internal consistency, based on average correlation among items.

The experiment was initially conducted with 39 subjects. To evaluate the reliability of the subject responses, an inter-rater reliability test was applied to appearance of the objects in each box from one to four, compared to the object in the reference box. Before each evaluation process, the definitions of hue, brightness, and saturation were read aloud from a text. By defining the terms, the subjects became aware of the evaluation criteria and possible confusions were omitted.

The box with a “point one” means, “it is the box that successfully illuminates the object that has the same or closest appearance as if it is in the reference box”. The “point four” means farthest.

The objects were located at the center of each box and the subjects were asked to fill out the survey leaflet. For each experiment phase, the created light was changed when the subjects completed their evaluation of the specified color (see Appendix E for the photographs of each scene for each color).

Due to the tripled nature of the RGB mixture method, measurement devices cannot calculate the photometric properties of the total radiation directly, since there are three different sources emitting light of different ratios. In that case, indirect measurement of the light reflected from a Barium Sulfate[13] coated surface provides the correct results.

4.4. THE PROCEDURE OF THE EXPERIMENT

The experiment was conducted for three days and only one subject was tested at a time. The average test duration was approximately 20 minutes. To test whether the subjects had any ophthalmologic problems, a color blindness test was conducted with pseudoisochromatic plates. Any kind of eye deficiency or color blindness of a subject would effect the perception of colors under different lights. To prevent any possible bias, the four boxes were shuffled, so that the subjects were not aware of any changes in one box in a constant position (see the Table 3.3: Shuffling Order of the Experiment Boxes on Page 60). The subjects were asked to turn their backs, while the boxes are shuffling. On the other hand, they were informed that all the five objects were painted with the same color. Each subject had eight survey leaflets, prepared specially for the colors they were going to evaluate. A sample survey leaflet can be found on Appendix F. On each leaflet, there were questions that were aimed to be evaluated by the three standard attributes of visual sensation: hue, brightness, and saturation. Each subject was asked to evaluate these three criteria for each color, by ranking the

[13] Barium Sulfate is a diffuse white reflective coating that offers greater than 97% reflectance between 450 and 900nm.

Figure 4.19. The DP101 Data Processor

In the laboratory, the CS100 and DP101 were connected and the created lights were measured. As seen in Figure 4.20, the devices were measuring a light, created by some LED clusters.

Figure 4.20. The Control Devices in the Laboratory

<u>The Calibration Palette</u>

The light measuring devices can measure light by direct or indirect method. The direct method measures the photometric properties of light directly from the light source, whereas the indirect method measures the reflected light from a reflective surface. In some cases, the direct method cannot be useful, since the light level of the source can extend to the upper limit of the lighting measurement device.

The luminance and chromaticity calculations of color televisions and CRTs, projection equipments and video projectors can be conducted by using this device.

A CS 100 Chromameter from Minolta, serial number of 19013037, was used to control and measure the created lights. The device gives two major data: the illuminance and Chromaticity Coordinates. (Figure 4.18)

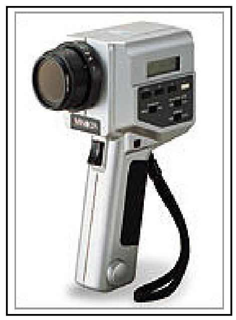


Figure 4.18. The CS100 Chroma Meter

The Data Processor

By using the Data Processor (DP-101), measured values can be calculated in terms of Yxy, L*a*b*, Color Temperature, and Correlated Color Temperature as the distance from blackbody locus Δuv for absolute color values. DP-101 has memory space for up to 300 sets of measurement data and a built-in thermal printer for printing out data, either at the time of measurement or from memory at a later time. In the experiment, the DP-101 with a serial number 331064 was used for data storage and printouts (Figure 4.19).

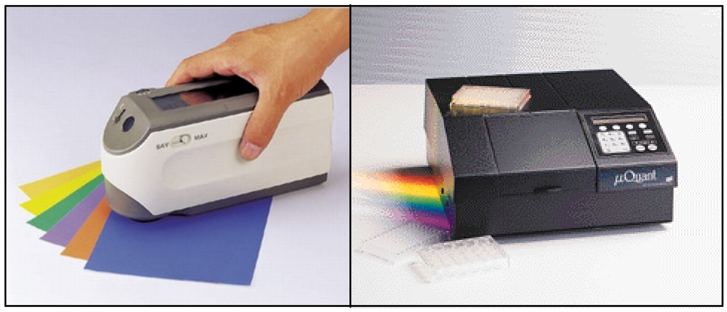


Figure 4.17. Two Examples for Spectrophotmeters, Konica Minolta CM-2600D, and µQuant™ Universal Microplate Spectrophotometer.

The surface color of an object can be measured by a spectrophotometer in few seconds and CC values are obtained simultaneously. These coordinates can be kept in computers that are attached to the device or printed out as a hardcopy. Every spectrophotometer measures the CC values of object and if desired, the output can be converted into other standard color spaces.

The Chromameter

The CS 100 Chromameter is used for measuring the Chromaticity Coordinates and luminance of the light sources and surfaces. It can measure luminance and chromaticity of small light sources, such as LEDs or miniature neon lamps. It can also be useful for measuring luminance and chromaticity of general light sources, such as tungsten lamps or fluorescent lamps. This device is widely used in calibrating the luminance and chromaticity of traffic signals and emergency exit lamps. The Chromameter is useful for reflective subject measurements of objects that cannot be measured by contact methods, such as distant building walls, painted surfaces, subjects with complicated shapes, or surfaces that should not be touched for sanitary reasons. One major field of use of CS 101 is in display measurements.

They were young subjects, having healthy vision and an architectural education of a certain level. 74% of the students had courses related to color in their education, while 26% of the subjects worked with primary colors in their first year students.

Before the test, they were asked about visual defects. Subjects with eye deficiency were asked to use their correction equipments, like glasses and lenses. Also, their color discrimination and vision abilities were tested before the experiment by pseudoisochromatic plates.

4.3.3. THE CONTROL DEVICES

The Spectrophotometer

The conversion tables and programs determined the CC values of the objects in the experiment. However, working with genuine museum artifacts, it is not possible to have color-notated objects. In that case a spectrophotometer can measure the CC of the surface of the object. By using such a device, the color of a specimen can be measured according to a variety of standards[12] like XYZ, L*a*b*, RGB, CMYK, and Y*xy*. There are portable and tabletop type spectrophotometers, like the ones shown in Figure 4.17. Museums can afford to buy them for their laboratories, or they can borrow from other institutions. In some cases, other museum laboratories could help them and answer their needs.

---

[12] Like CIE 1931 Y*xy* color space, the XYZ, L*a*b*, RGB, and CMYK are different kinds of color spaces that were out of scope of this study.

DALI system, designed for the experiment, are drawn schematically in Figure 4.15.

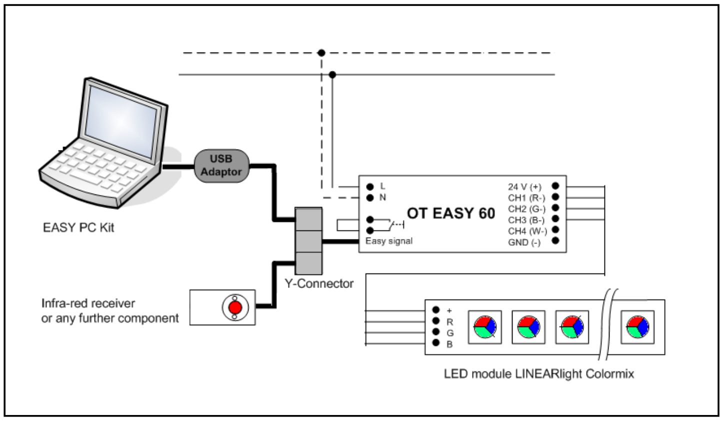


Figure 4.15. A Schematic Drawing of the DALI System Created in the Experiment.

4.3.2. THE SUBJECTS

The experiment was conducted with 34 university students. The gender distribution of the subjects is 19 female and 15 male subjects, having an average age of 21,08. Majority of the subjects (44%) were 21 years old and 59% of them were second year students. Figure 4.16 shows the detailed presentation of the age group and class of the subjects in percentage.

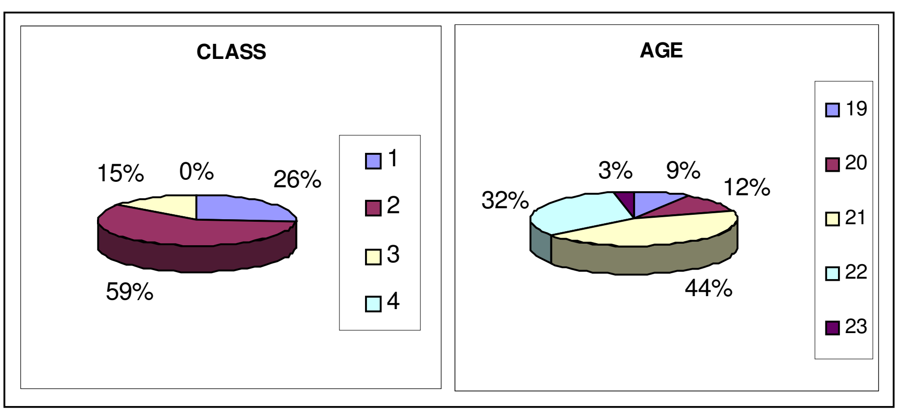


Figure 4.16. The Percentage of the Age Group and Class of the Subjects.

The DALI System

In the DALI systems, the software for a dynamic color control controls the intensities of red, green, and blue LEDs individually. By using this software, intensity of each LED can be increased or decreased. The CC of the white light can be measured by using a chromameter that measures the photometric properties of the light source. Increasing or decreasing the intensities of the red, green and blue LEDs should be done by a computerized system. In this study, an experiment was conducted previously, by using manual dimmers. However, imprecise CC values were obtained with difficulty after numerous attempts. This experience showed the necessity of a computerized system. A DALI system, based on computers and precise adjustments of the light levels of each LED, increased the reliability of the experiments.

To create the desired lights, The EasyColor Control software and DALI systems of OSRAM were used. The screenshot of the EasyColor Control is shown in Figure 4.1, on page 44. The software was installed on a computer with Intel Pentium IV 3.06 MHz processor and 512 MB RAM memory.

The main device of the DALI system from OSRAM was OT Easy 60. Its initial purpose was to connect the computer with the LED clusters. The second purpose was to provide an electric current for the DALI circuit. The connection diagram and the names of the necessary parts of the OSRAM

The shuffling order of the boxes for the eight colors is listed in Table 3.3.

Table 3.3. The Chosen Colors and the Shuffling order of the Experiment Boxes

Color Number	NCS Notation	Shuffling Order			
		1st Box	2nd Box	3rd Box	4th Box
1	S3020-G50Y	B3	**BD**	B4	B6
2	S3060-G50Y	B3	B4	**BD**	B6
3	S3020-Y50R	B3	B4	B6	**BD**
4	S3060-Y50R	**BD**	B4	B6	B3
5	S3020-R50B	B3	**BD**	B4	B6
6	S3055-R50B	B3	B4	**BD**	B6
7	S3020-B50G	B3	B4	B6	**BD**
8	S3055-B50G	**BD**	B4	B6	B3

B3: The box with the 3000 K LED
B4: The box with the 4200 K LED
B6: The box with the 6500 K LED
BD: The box with the Desired CC

Figure 4.14 shows a photograph of the experimental setup. The boxes and the sitting position of the subjects were carefully adjusted.

Figure 4.14. The General View of the Experimental Setup.

in the experiment. These delicate palettes are used to measure the photometric properties of the light sources. By using the small pegs on the slanted surface, the palettes were securely fixed. In Figure 4.11 and 4.12, the slanted surfaces can be seen.

The five boxes were located with a polar array, to provide equal lines of sight for the subjects. The schematic drawing of this layout can be seen in the plan drawing of the experiment room in Figure 4.8. Each spherical object and box had identical visual conditions. The reference box on the left, containing the D65, was separated by 10 cm from the other four boxes. The electric cable layout was designed to be flexible, to allow shuffling the boxes. The box with the created light should be methodically shuffled with other three boxes with 3000, 4200, and 6500 K LEDs, to reduce any possible bias of the subjects (Figure 4.13).

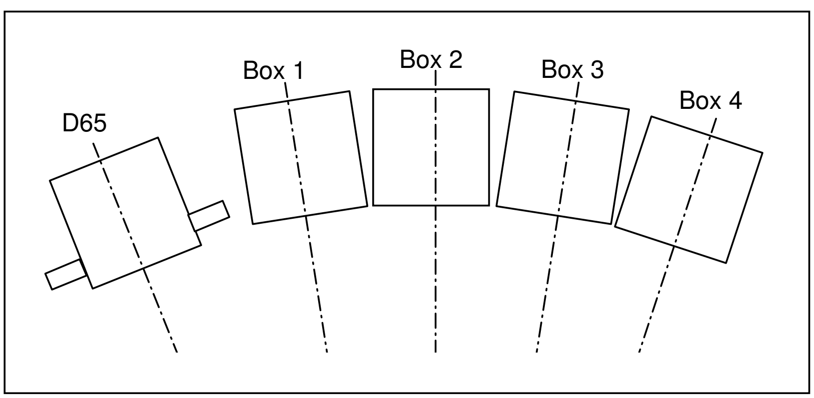


Figure 4.13. The Schematic Drawing of Five Boxes.

identical boxes, and if the reference box were wider than the other four boxes, than the subjects would be biased. On the other hand, if all the five boxes were of 65 cm width, then the total experimental setup would need to be at least 325 cm long. This would exceed the cone of vision of the subjects. The solution was to fulfill the requirements of the experiment by modifying the fifth box. Two holes with, 5 cm diameter, were drilled on both sides of the boxes. The two ends of the fluorescent tubes protruded from the box. To avoid direct glare and hide the unwanted light outside the box, plastic tubes were applied to two edges of both. In Figure 4.12, the technical drawing of the reference box is shown.

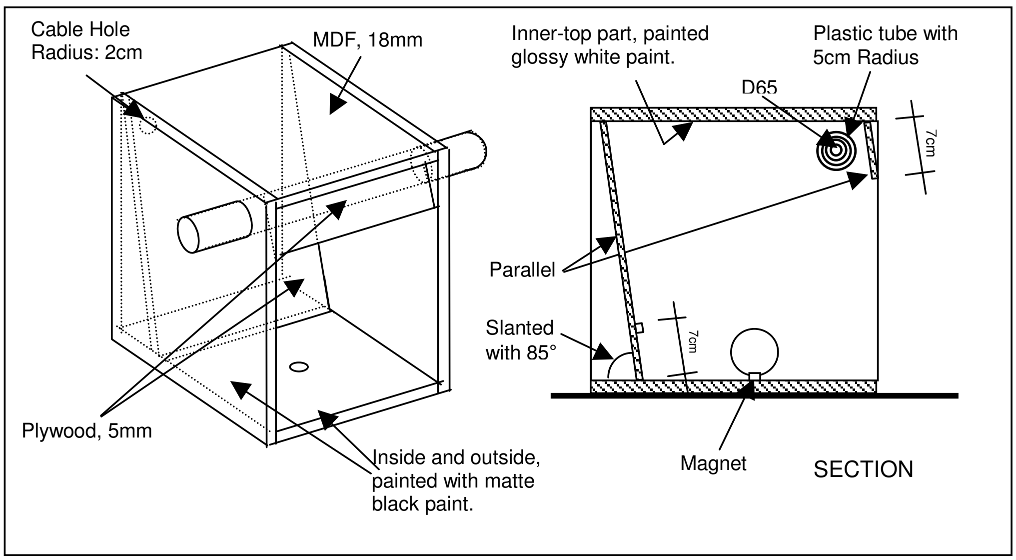


Figure 4.12. The Technical Drawing of the Reference Box.

The backgrounds of the boxes were slanted at 85 degrees. There were two reasons for this. The first was to provide a better inter-reflection of the light rays, coming from the LEDs that were also fixed on the slanted surfaces. The background of the boxes and the LED bases were parallel to each other. The second reason was to provide a secure base for the calibration palettes used

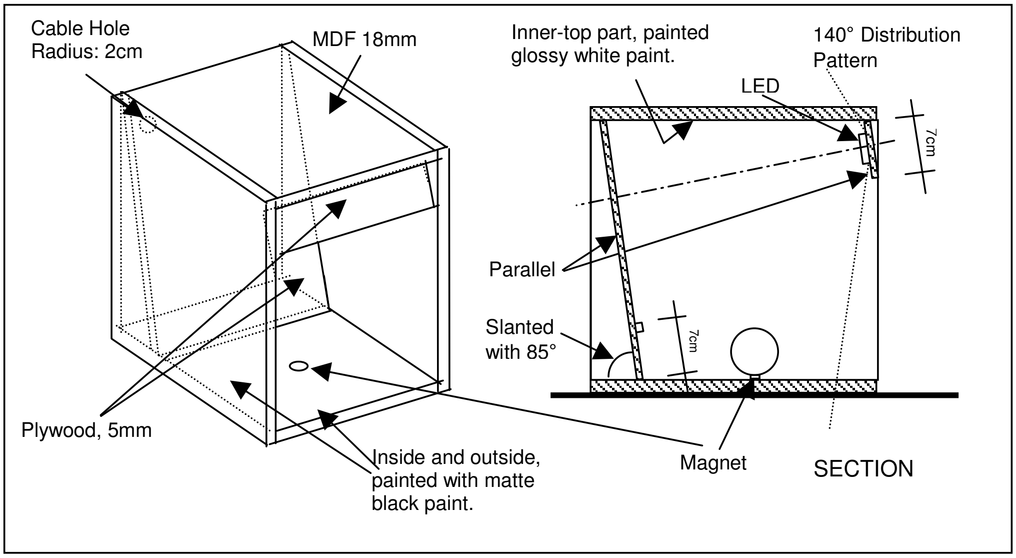


Figure 4.11. The Technical Drawing of the Boxes

Four identical boxes were produced and two types of LEDs, the LINEARlight Colormix LED module from OSRAM that is used for creating lights with desired CC values, and the three LEDs from Tridonic-Atco: the P108 warm white (WW-3000K), neutral white (NW-4200K), and daylight (DL-6500K) LED were installed into those boxes at same angle and same position.

A fifth box, with a D65 reference light source, was designed for the experiment. The dimensions and design of that box was similar to the other four boxes, however, the main difference was the cylindrical additions for the light source.

The D65 is a linear fluorescent light source and in the experiment, the smallest D65 in the market with 58 cm length, was used. This length increases to 62 cm with the electrical wirings and fixing equipment, so the experiment box should be at least 65 cm wide. The aim is to have five

The Boxes

LEDs and test objects were installed in the identical boxes, having same color and dimensions. These boxes were specially designed for the experiments. To prevent the undesired inner reflections, inner surfaces of the boxes were painted with a matte black paint. The black paint also enables viewers to separate the object from the background, and lets them concentrate on the illuminated object. Although in museums, objects are generally viewed in front of surfaces that are covered with materials having mid-gray toned colors, the aim of this dissertation was not to test the relation of the illuminated object to the background. Another reason was the nature of the light itself. The lights in each box had different spectral properties and they would illuminate the backgrounds differently from each other. The only surface that was painted with glossy white paint was the inner-top part of the box. The subjects could not see that portion of the box. This white paint increased the amount of reflected light that is being emitted from the LEDs. The technical drawing and dimensions of a box is given in Figure 4.11. More detailed drawing of the box is included in Appendix D.

The D65

A light source is different from an illuminant. A light source radiates certain wavelengths, mainly in the visible portion of the spectrum, such as a candle or a tungsten filament bulb. Any light source can be considered as an illuminant, unless it fulfills certain specifications. There are several illuminants such as A, C and D65. The illuminants A and C were defined by the CIE in 1931 to represent tungsten light and natural daylight respectively. Illuminant C was replaced by D65 because it contains insufficient energy at lower wavelengths.

A typical D65 is an illuminant with a Correlated Color Temperature of 6504 K and its Chromaticity Coordinates are specified as x, y = 0.313, 0.325 (IES, 1984, p. 5-27).

For the experiment a D65 simulator was obtained from Verivide. This firm designs and manufactures fluorescent light simulators for color viewing, measurement and control in the textile, fashion, and food industry. The D65 was calibrated as a reference illuminant for color matching and has a certificate for BS 950 Part 1:Artificial Daylight for the Assessment of Color that defines the tolerances in chromaticity and spectral distribution of an illuminant representing a phase of daylight suitable for color matching and color appraisal (“BSI BS 950,” n.d.).

software had been installed. The computerized LED adjustment system used LINEARlight Colormix LED modules, having three LEDs inside individual epoxy encapsulants. They had a uniform light distribution pattern with 140 degrees, without producing UV or IR radiations. The LED clusters were attached to the experiment boxes. All the wiring and application procedures were done according to the instructions of the manufacturer (Figure 4.10).

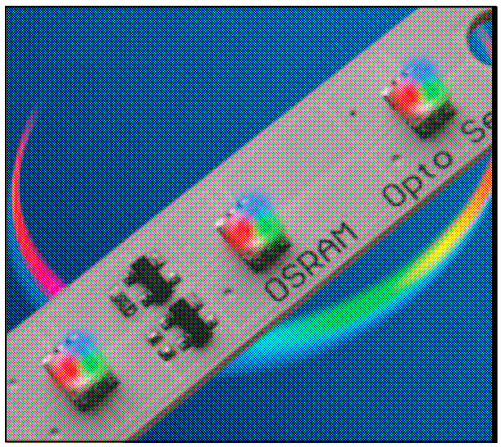


Figure 4.10. The LINEARlight Colormix LED modules

2. P108 warm white (WW), neutral white (NW), and daylight (DL) LED modules from Tridonic-ATCO, represented the commonly used LEDs in the market, with Correlated Color Temperatures of 3000, 4200 and 6500 K. However, they were not connected to a DALI system, because they emit constant white light at certain Color Temperature.

The spheres, originally designed as ping-pong balls, were mass produced items with 40 mm diameter. Different from other conventional ping-pong balls, these special balls used in the experiment have no connection joints on their surfaces. This reinforces their spherical appearance and allows the subjects to evaluate a colored sphere, rather than painted ping-pong balls. During the experiment, 40 balls were used and they all had to be located at the same position inside the experiment boxes. To enable this, brass-plated steel rivets were fixed at the bottom of each ball. These metal pieces were magnetically connected to the bottom of each experiment box. These magnets allow each ball to be easily located at pre-defined spots in the boxes (Figure 4.9).

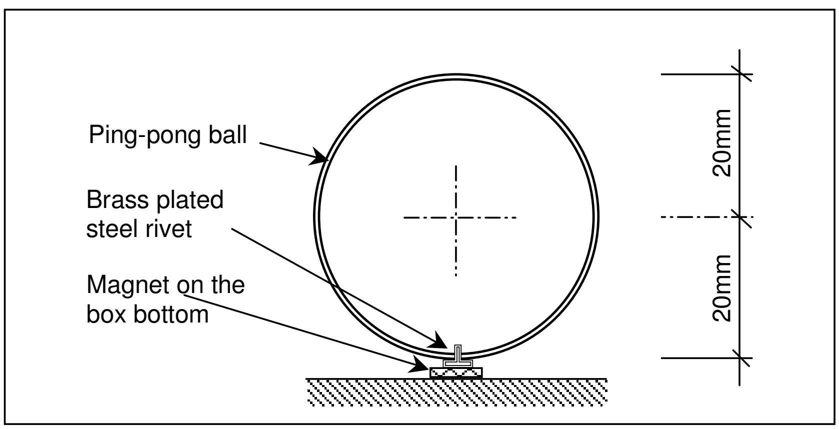


Figure 4.9. The Section Drawing of one of the Balls, used in the Experiment.

The LEDs

In the experiment, there were two types of LEDs for different purposes:

1. The LINEARlight Colormix LED modules from OSRAM: They were used to create the light with desired Chromaticity Coordinates. They were connected to a computer on which the EasyColor Control

The Objects

In a museum, every object can be an artifact in the display cabinet. From stone to silk and from glass to gold, the number of museum objects is as varied as the number of materials in the world, and as diverse as the imagination of the humankind. Although they may have different material, size, shape, texture, and color, many art objects are extremely sensitive to light-based damages.

The objects in museums are different from each other in form, texture, and color. Highlighting or concealing the form and texture can be achieved by different techniques of lighting that were outside the scope of this study. Color, or in more general terms, the total effect of chromaticity and luminance, is the key feature that was studied in this dissertation.

In the experiment, while choosing the samples, some constraints limit the number and type of the objects, to a certain degree.

The purpose of the experiment is to test the validity of the method based on the relation between the light and the appearance of the object. Thus, the objects have to be identical in both form and size. Complicated forms would create problems in perception of the third dimension, due to uncontrolled shadows or highlights. Their geometric shape, a sphere, was chosen as a non-complicated three-dimensional form.

4.3. THE MATERIALS OF THE EXPERIMENT

This part of the study describes the setting, objects, equipment, and subjects of the experiment.

4.3.1. THE SETTING

An experimental setting was designed to test the method that is proposed in this study. The experiment was conducted in the Building Physics Laboratory of Bilkent University. The room dimensions were approximately four meters by five meters. There were no windows, so daylight penetration is prevented. The schematic plan drawing of the experiment room is shown in Figure 4.8.

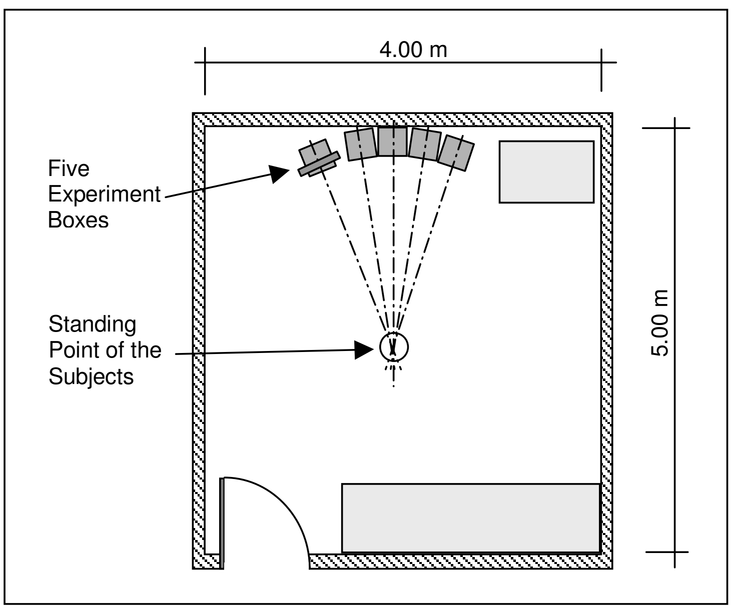


Figure 4.8. Plan of the Experiment Room.

The most critical phase of the proposed method is to find the Chromaticity Coordinates of the objects that are chosen to be illuminated with specially created light sources. In this study, colors with pre-calculated CC values were used. However, the color samples were sent to a laboratory and they were measured with Datacolor Check Plus spectrophotometer. They are very close to the pre-calculated values, listed in Table 3.2. This shows the validity of both the NCS to CC conversion program and color choosing methodology of this study.

Table 3.2. A Comparison of the Chromaticity Coordinates of the Chosen Objects, Obtained from the Spectrophotometric Measurements with the Values Obtained from NCS Conversions.

Color Number	NCS Notation	CIE Chromaticity Coordinates Converted from **NCS Values**		CIE Chromaticity Coordinates Obtained from **Spectrophotometric Measurements**	
		x	*y*	*x*	*y*
1	S3020-G50Y	0.34058	0.39193	0.3420	0.3895
2	S3060-G50Y	0.39662	0.50714	0.4083	0.4985
3	S3020-Y50R	0.38702	0.36591	0.3814	0.3621
4	S3060-Y50R	0.51208	0.39465	0.5071	0.3950
5	S3020-R50B	0.30640	0.29339	0.3046	0.2991
6	S3055-R50B	0.30344	0.19844	0.3087	0.2046
7	S3020-B50G	0.27835	0.33127	0.2808	0.3352
8	S3055-B50G	0.18941	0.33695	0.1903	0.3409

The selected colors and their CIE Chromaticity Coordinates conversions are in Table 3.1.

Table 3.1. The Chosen Colors and their Chromaticity Coordinates.

Color Number	NCS Notation	CIE Chromaticity Coordinates	
		x	*y*
1	S3020-G50Y	0.34058	0.39193
2	S3060-G50Y	0.39662	0.50714
3	S3020-Y50R	0.38702	0.36591
4	S3060-Y50R	0.51208	0.39465
5	S3020-R50B	0.30640	0.29339
6	S3055-R50B	0.30344	0.19844
7	S3020-B50G	0.27835	0.33127
8	S3055-B50G	0.18941	0.33695

While choosing the colors, the purpose was to test the applicability of the method, both for the objects that had a CC on the isotemperature lines and CC on the outer region of the curved area. Although this was a constraint on choosing the object, the proposed method should be applicable for all the objects with CC, plotted anywhere on the CIE Diagram (Figure 4.7).

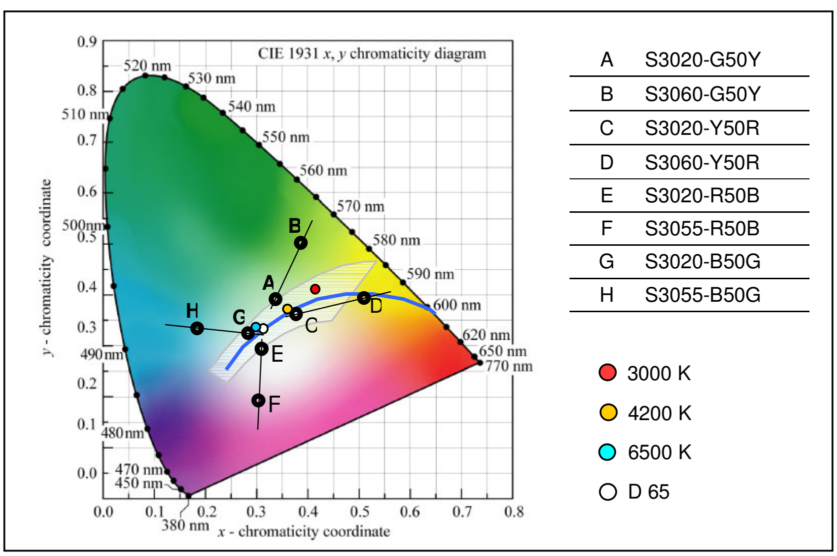


Figure 4.7. The Chromaticity Coordinates of the Color Samples Plotted , on the CIE 1931 Chromaticity Diagram Iso-Temperature Lines.

that, while the G50Y and Y50R group colors have Chromaticness of 60, R50B and B50G have Chromaticness of 55.

Figure 4.5. The Selected Color Pairs and their NCS Notations.

The Chromaticity Coordinates of the selected colors were found by using computer software. The Easy RGB© software is useful for the conversion of the color order systems and finding the CC of any given color. On the screenshot of the Easy RGB software, note the sample color notation S 3020-B50G, its CC, and other equivalent values (Figure 4.6).

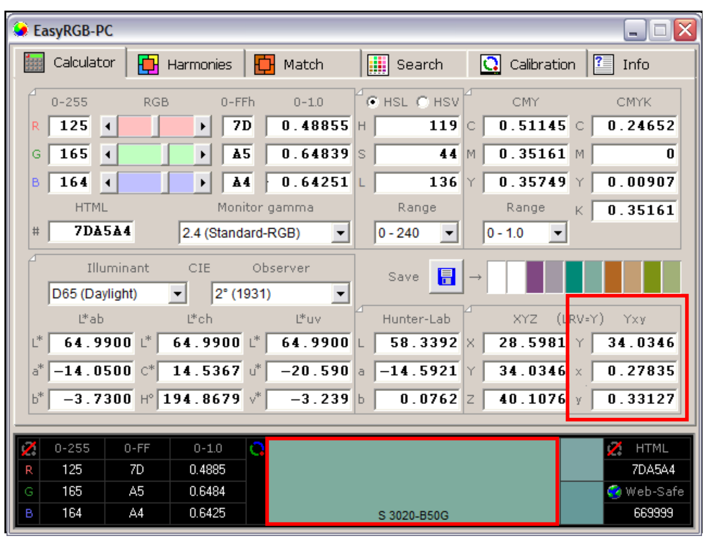


Figure 4.6. The Easy RGB Color Conversion Software.

© Easy RGB is a trademark of Logicol s.r.l.

Each of the main color groups has sub-colors, notated on NCS Color Triangles. The sub-colors on these triangles are grouped according to their whiteness, blackness, and chromaticness. The methodology for choosing the colors in the experiment was to take blackness constant for each color and to obtain colors with different chromaticness and whiteness. Constant blackness enables to obtain colors locating on a virtual axis, directing to the center of the CIE diagram. The colors in the experiment were chosen from group of colors that have a common blackness of 30 and chromaticness of 20 and 60. The color choosing methodology is illustrated on an example NCS Color Triangle in Figure 4.4.

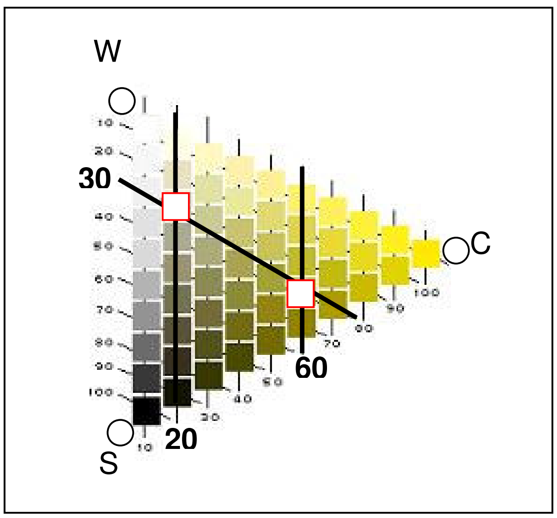


Figure 4.4. The Schematic Drawing of Color Choosing Methodology.

The identical objects were painted with the color pairs, as illustrated in Figure 4.5[11]. In an NCS Color Triangle, some colors have no certain whiteness, blackness or chromaticness. This is due to the nature of the colors, their wavelengths, and certain mechanics of human perception. Note in Figure 4.5

[11] The actual colors may look different from the printed colors.

The Method for Choosing the Colors

Although the first phase of the proposed method employed a spectrophotometer to obtain the CC of the surface colors, using well-defined and universally notated colors in the experiment reinforced its validity and replicability. Since colored textiles, natural artifacts or earthenware jugs of different surface properties can be considered as a section of typical museum objects, they would broaden the scope of the study and can be considered as experiment samples for further studies.

For the experiment, NCS notated primary colors were chosen. Yellow, red, blue, and green; the four primary colors are not generally experienced in museums. The intermediate color groups, those having 50% of their neighboring primary colors, were preferred to test more reasonable museum colors. Y50R, R50B, B50G and G50Y are the names of the main color groups that have equal amount of NCS primary colors: for instance Y50R had 50% yellow and %50 Red (Figure 4.3)

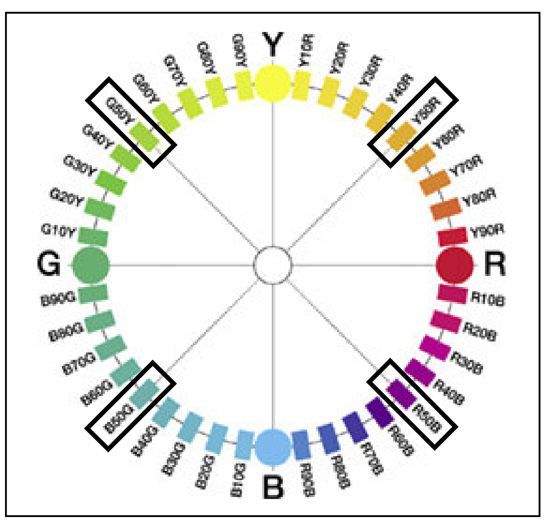
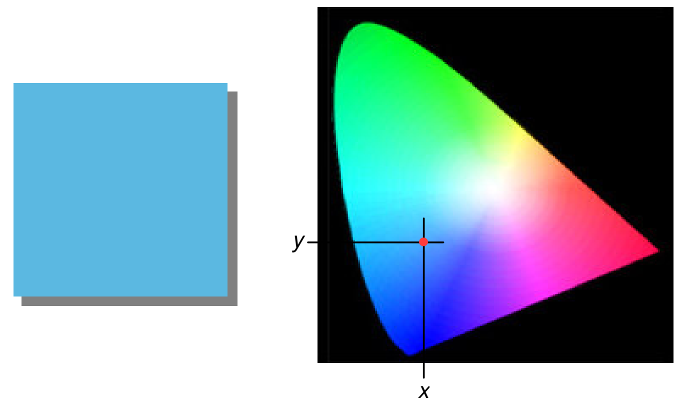


Figure 4.3. The Illustration of Main Color Groups.

ratios of three primaries accordingly, the required light can be obtained (Figure 4.2).



R: 91, **G**: 184, **B**: 225 = ***(x,y)***: (0.2280, 0.2748)

Figure 4.2. The Conversion of RGB Parameters into (*x*,*y*) Coordinates.

<u>To Measure and Control the Created Light</u>

The control devices measured the CC of the each created light. Every measurement identified a certain *x* and *y* value for that specific trial. By using this result, the RGB values were readjusted until the desired coordinates were obtained. The creation of the light and measurement of it cannot be separated from each other. These two phases have to be conducted at the same time.

4.2. THE COLORS IN THE EXPERIMENT

To test the method in the most proper way, an experiment was conducted with homogeneously colored objects. The spherical objects were painted with special colors that were selected by a certain procedure.

by mixing the three primary colored LED clusters. The RGB LEDs, as indicated earlier, use the Additive Color Mixing principle. However, to create the desired light, the three primary colors had to be mixed a certain amount by DALI systems. The RGB amounts and other parameters can be saved in the computer memory, or another kind of mass storage medium, and can easily be recalled whenever they are required. In Figure 4.1, a screenshot from the EasyColor Control Software from OSRAM that was used in the study is shown. The RGB adjusting channels and the symbolic illustration of the created light is indicated by red rectangles.

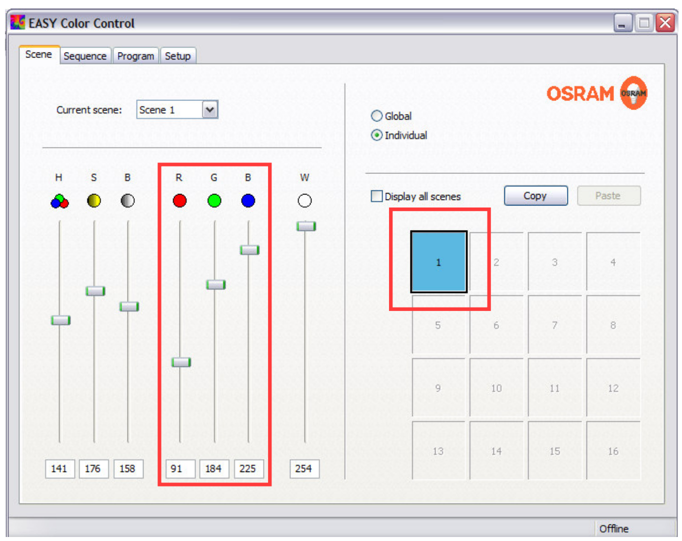


Figure 4.1. The Easy-Color Software from OSRAM.

The three primaries of light: red, green, and blue, have to be adjusted to create a light that represents a coordinate in the CIE Chromaticity Diagram. Although the adjustment of light seems a difficult and challenging process, a skilled designer can adjust the light, after a few attempts. By changing the

Adjusting Chromaticity Coordinates of LEDs to Create the Light

After obtaining the *x* and *y* coordinates that defines a specific point on the CIE 1931 Chromaticity Diagram, curators or lighting designers in the museum can create special RGB LED arrangements. As any other custom made productions, creating a light that has the same CC as the object can be a difficult process. However, the museum objects are unique and the primary aim of a museum is to create the best possible display platform for them.

In the experiment, there were two important issues when adjusting the Chromaticity Coordinates of LEDs:

1. Create a light by using the computer software of a DALI system by adjusting the intensities of three RGB LED clusters.
2. Measure and control the CC of the light that is produced during these attempts.

These two issues should be taken into consideration at the same time, and the light must be measured and controlled at that moment it is obtained.

To Create the Light

In the experiment, eight colors for the eight specific object groups were located under five different light sources. Four lights were constant light sources of certain photometric properties. However, using the CC values that were obtained from the surface properties of the objects, created the fifth light. Easy-Color software from OSRAM was used to create this special light

4. EXPERIMENTAL STUDY

4.1. THE METHODOLOGY OF THE EXPERIMENT

There are two phases of the experiment: obtaining the Chromaticity Coordinates of the object, and adjusting the RGB LED clusters to create a light of that CC value.

Obtaining Chromaticity Coordinates of the Objects

Working with real objects, the first phase of the proposed method in a museum is to obtain the CC value of the objects, by using a spectrophotometer. The detailed description of this specific measurement instrument is given in detail in the following parts.

However, in the experiment, the CC values of the surfaces were known. The paints with NCS codes were pre-calculated, and their CC values were converted by using a conversion program. The CC of the colors were also measured by spectrophotometers and obtained similar results, matching the values in conversion programs. The colors and their CC values are explained on the further parts of the study.

Although his findings guided many other perception-oriented studies, the spectral properties of the light sources were disregarded. It is impossible to think of an increase in the luminance level of a colored object solely, without considering the spectral properties of the light source that illuminates its surface.

Approximately one decade later, two scientists, J. C. Stevens and S. S. Stevens (1963), worked more on the Hunt Effect and developed a new outcome, called the Stevens Effect. The Stevens Effect studies the change in saturation due to the change in the luminance level. Different from the Hunt Effect, this increase in contrast has been examined closely in their studies. Their studies showed that as the luminance level increases with the Color Temperature of the light source, saturation of the colored surfaces increases also. As the luminance level increases, the bright colors tend to look brighter -saturated, and dark color tends to look darker-unsaturated. Therefore, as the luminance level increase, the rate of change between the saturation of dark and light colors increases.

This effect shows the relation between the change in the spectral properties of the light source and the perception of the color of the object.

findings, Anstis (2002) conducts several experiments on the effect of light to dark and dark to light adaptations of the Purkinje Shift and concludes that "cone vision gradually switches to rod vision during dark-adaptation, the peak of visual sensitivity shifts towards shorter wavelengths, and blue colors look relatively lighter than reds" (p. 2486).

The level of illuminance affects both the brightness of the object and visual mechanisms of the human eye. By increasing or decreasing the light level, or by changing the spectral properties of the light sources, the appearance of the object changes dramatically.

3.3.3. EFFECTS ON SATURATION

The third major attribute of visual sensation is the saturation. It is a visual sensation that permits a judgment to be made of the proportion of pure chromatic color in the total sensation (CIE, 1970, p. 45-25-225).

R. W. G. Hunt (1952) studies on the perception of color by the human eye. His findings are known as the Hunt Effect. This phenomenon states that, as the illuminance from a light source increases, the luminance and its saturation increases. Hunt concludes his findings as:

> 1. As the adapting light intensity is lowered, colors gradually become increasingly unsaturated.
> 2. At low levels of adapting light intensity, the saturation increases with increasing test-color intensity.
> 3. At high levels of adapting light intensity, increasing the test color intensity caused most colors to become bluer.
> 4. The sensation corresponding to dim light seen by the dark-adapted eye is pale blue, not colorless (p. 49).

produced by increasing the purity of a color stimulus while keeping its luminance constant within the range of photopic vision (CIE, 1988, p.50). Nayatani (2000) conducts several experiments on the effect of light on the brightness of the object and his works on achromatic samples concludes that by increasing the illuminance for a series of achromatic color samples from white to black, that there was a significant difference between brightness and whiteness-blackness preference. In the research field of the effect of light on the brightness of the object, the literature mainly built on the Opponent-Theory. According to that theory, black and white samples are perceived as dull white and dull black in a dark room at low illuminance, and they were perceived as clear white and clear black at high illuminance ("Ewald Hering," n.d.). Emitting more or less light affects the appearance of the color of the object.

The human eye is responsible for the recognition of the optical stimuli, and the change in the luminance level affects the human visual mechanism. When the light level decreases, the ability of vision decreases due to the physiological facts of the human eye. At low illumination levels, the peak sensitivity of the human eye shifts towards the blue end of the color spectrum. This phenomenon is called The Purkinje Effect[10]. Wald and Griffin studied this phenomenon earlier in 1947. They studied the visual mechanisms of the human eye in dim and bright lighting conditions, and they concluded that the Purkinje Effect is "related to the adaptation of the human eye as well as the receptor cells in the retina" (p. 326). In addition to their

[10] This shift is also known as The Purkinje Shift of Purkinje Dark Adaptation and discovered In 1825 by the Bohemian physiologist Johannes Evangelista von Purkinje.

differences in the case of highlight and concealing surfaces of a real object. Pridmore, Huertas, Melgosa and Negueruela (2005) conduct several studies on Bezold-Brücke Shift. They work on this phenomenon in the color variability of liquids in a transparent medium. According to them, the Bezold-Brücke Shift can be observed in translucent liquids of any hue. They give an example of a blue liquid being observed in sunlight. At its lightest parts, the color of the liquid tends to change to slightly greener appearance. They also suggest that for all other hues of any translucent or opaque materials, any such wavelength shifts would be in the same direction.

3.3.2. EFFECTS ON BRIGHTNESS

Brightness is defined as the attribute of a visual sensation, accordingly an area appears to emit more or less light (CIE, 1970, p. 45-25-210). Brightness is also explained as the perceived amount of light reflected from a surface, and its colorimetric equivalent is the luminance. By increasing or decreasing the illuminance for a colored object, its brightness increases or decreases revealing the overall reflected light from the object.

Melgosa, Rivas, Hita and Vienot (2000) conducted several studies of the relation between the color attributes and the human visual system. They defined the results in the variation of brightness as an outcome of the Helmholtz–Kohlrausch Effect. In the CIE terminology, the Helmholtz–Kohlrausch Effect is defined as the change in brightness of a perceived color, The quality of light directly affects the appearance of the hue of the surface, and resulting in two major phenomenon: the Abney Effect and the Bezold-Brücke Shift.

The Abney Effect relates to the clear gradual shift in hue preference, when a white light is added to a monochromatic light. As Johnson and Fairchild (2005) clarify, straight lines in a chromaticity diagram, radiating from the chromaticity of the white point to the spectral locus, are not lines of constant hue. When white is added to a color, it gradually shifts to its tint. A very common example of Abney Effect can be experienced in the nature. On a sunny day, at the beach, the deep water appears dark blue, whereas the water near the shore appears light blue. The light colored sands reflect the daylight and by adding white to the appearance of the hue, the water looks light blue.

Unlike the Abney Effect, the Bezold-Brücke Shift is a change in hue perception as intensity changes. The wavelength of monochromatic light sources is not the only indicator of the perceived hue. As the level of luminance changes, the perceived hue of the object also changes.

Pridmore (2006), in his study on the effects of light on hue, concentrated on the Bezold-Brücke Shift. He notes that this hue shift is valid not only for the aperture colors, but also for the object colors. For him, both Abney Effect and Bezold-Brücke Shift effect the perception of three-dimensional objects, by adding hue-shift differences to lightness and chroma

3.3. EFFECTS OF LIGHT ON THE ATTRIBUTES OF VISUAL SENSATION

To understand the complicated nature of the visual sensation of human beings, as Pridmore (2007) suggests, one must combine the effort of many disciplines such as physics, optics, chemistry, genetics, biology, and anatomy. Although each of these disciplines can investigate the nature of human visual system inside their own research fields, this dissertation concentrates on the psychophysics of color appearance. Psychophysics, as Ventura (2002) defines, investigates the relationship between physically measured stimuli, in this case the light, and the perceptions of those stimuli by the visual sensation of human beings.

The effects of light on the attributes of visual sensation can be investigated regarding three outcomes: hue, brightness, and saturation.

3.3.1. EFFECTS ON HUE

The term “hue” is defined as the attribute of visual sensation according to which area appears to be similar to one of the perceived colors: red, yellow, and blue, or, to a combination of two of them (CIE, 1970, p. 45-25-215). The color appearance of that area can only be achieved by a light source. In this definition, the light source that illuminates the area is not well defined. Since an object under sunlight may look very different under a fluorescent lamp, a definition for hue has to involve a certain degree of awareness of the light source.

S 1050-Y90R is a color notation in NCS. The letter “S” at the beginning stands for the “Standard”. In the two pair of numbers, 1050, the 10 is the blackness and 50 is the chromaticness. The letters and numbers after the dash symbol represent the hue of the color. In the example, “Y90R” means that the color has 90% red and 10% yellow. The whiteness is not shown in this notation, but it can be calculated as 100 minus 10 minus 50 equals to 40%.

In the NCS color notations, several systematic relationships between different colors can be established. The NCS Color Triangle is based on grouping the colors according to whiteness, blackness, and chromaticness[9]. In Figure 3.6, color samples that have same blackness, same chromaticness, and same whiteness, are illustrated with black lines. Note that the parallel black lines are 10 units interval in whiteness and blackness groups, whereas on the vertical chromaticness groups, the intervals below 10 are 05 and 02.

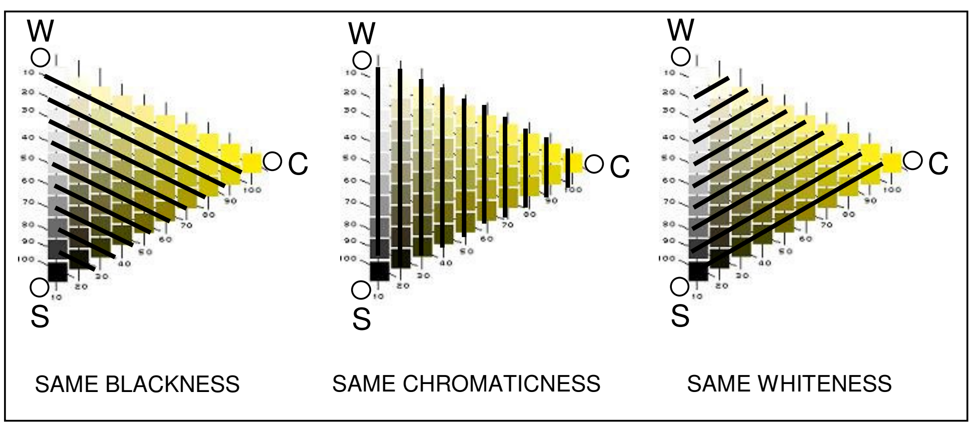


Figure 3.6. Color Samples with same Blackness, Chromaticness and Whiteness in NCS Color Triangle.

[9] There are three more groups, which the colors are grouped together: same nuance, same saturation, and same lightness. These three grouping criteria were out of scope of this study. For further reading visit www.ncscolour.com

To give an exact NCS notation of a color, a three-dimensional imaginary color space, the NCS Color Space, was created. It is a composite geometric form that includes the primary colors on the NCS Color Circle and composite colors on NCS Color Triangle (Figure 3.4).

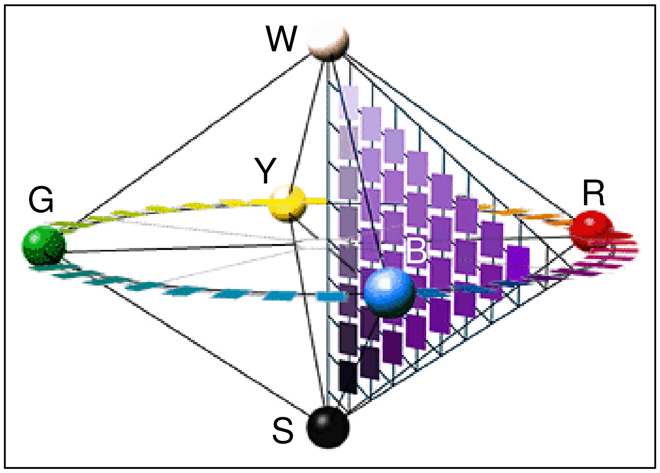


Figure 3.4. The Schematic Description of NCS Color Space

To clarify the NCS Color Space and color notations, it is necessary to give an example from the web page of NCS (Figure 3.5) ("The NCS System," 2002)

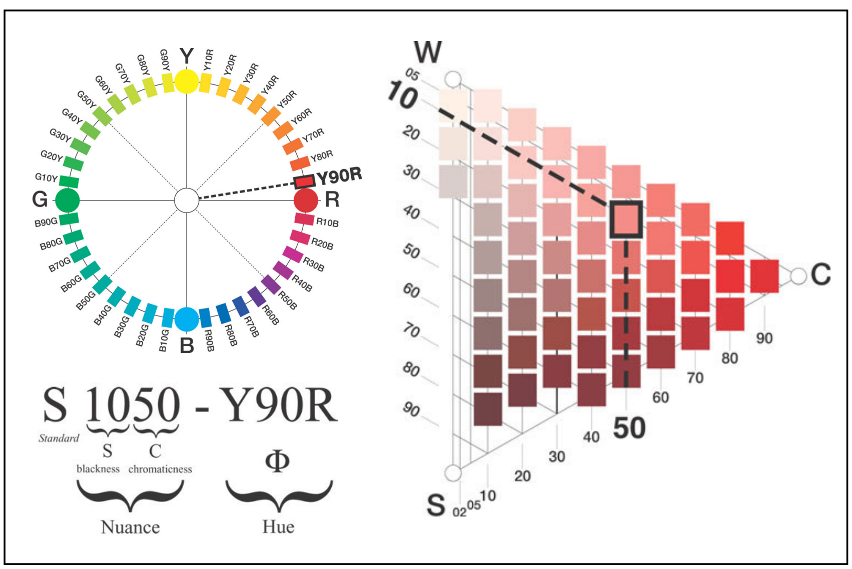


Figure 3.5. An Example Color Notation in NCS.

3.2. NATURAL COLOR SYSTEM

The Natural Color System (NCS), a color model developed by the Skandinaviska Färbinstitutet AB[8], describes the organization of the color sensations as perceived at the upper brain level. NCS is the reference standard of color designation in Sweden, Norway, and Spain and one of the standards used by the International Color Authority. It is, arguably, better fitted than other color models to observe experience of the humans and describe their color sensations. The NCS model is based on six elementary color perceptions as described by color opponency, comprising red versus green, blue versus yellow and black versus white. While the former two opposed pairs are for chromatic perception, the latter pair detects light-dark variation, that is, the illuminance. As seen in Figure 3.3, the primary colors of NCS are white (W), black (S), yellow (Y), red (R), blue (B), and green (G) and all other colors can be described in terms of their degree of visual resemblance to the elementary colors. These resemblances are the elementary attributes like yellowness, redness, blueness, greenness, whiteness, and blackness. NCS color notations are based on how much a given color resembles two or more of these six elementary colors.

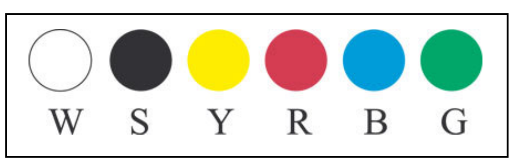


Figure 3.3. The Primary Colors in NCS.

[8] Translation: Scandinavian Color Institute.

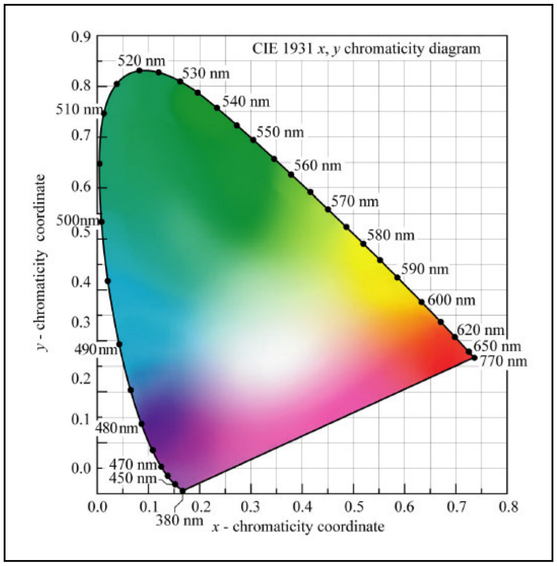


Figure 3.2. The 1931 CIE Chromaticity Diagram.

The outer edge of the horseshoe shape refers to the wavelengths of monochromatic colors. Note that the horizontal axis represents the *x* values and vertical axis represents the *y* values. Any point inside the horseshoe shape has a coordinate with *x* and *y* values.

The Color Temperature of the light source determines the color of white light, either warm or cold. The light source has a Color Temperature, if the CC are plotted on the Planckian Locus. In other cases, where the CC is plotted on isotemperature lines, the light source has a “Correlated Color Temperature”. In both cases, the light is considered as a white light.

In Appendix B, the CIE 1931 Chromaticity Diagram isotemperature lines are shown. The CC, plotted inside the curved shape is considered as a white light.

Among these color-order systems, NCS was chosen for this study, because of its reputation in the industry and other advantages that are described in the next part of the study.

3.1. CIE CHROMATICITY COORDINATE SYSTEM

The color perception of the eye is initiated by red, green, and blue cone cells on the surface of the retina. In classic color matching, these tristimulus primaries are mixed to create a color. Sometimes, to get the specific color, a primary has to be subtracted from the mixture. For instance, to create the monochromatic light with 540nm, a red primary has to be a minus value indicated with a letter “A” in Figure 3.1.

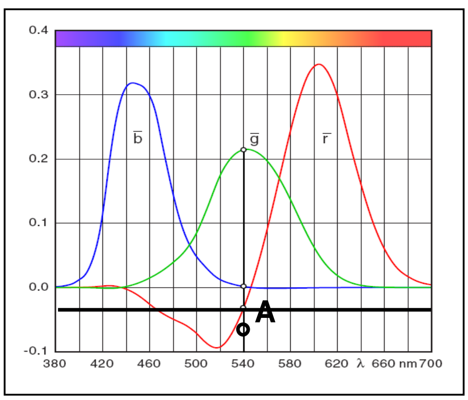


Figure 3.1. The Three Primaries, Adjusted to get a Wavelength of 540nm.

To avoid negative values, CIE introduced the Chromaticity Coordinate System. The CIE Y*xy* color space is based on direct measurements of human eye and it serves as the basis of many other color spaces. Figure 3.2 shows the 1931 CIE Chromaticity Diagram; this is an industry standard and is the common way of visualizing CIE tristimulus values.

3. THE COLOR-ORDER SYSTEMS

A color-order system, as Wyszecki and Stiles (1982) state, “is a rational method or a plan of ordering and specifying all object colors within a limited domain by means of a set of material standards selected and displayed so as to represent adequately the whole set of object colors under consideration” (p. 506).

There are three major color-order systems, developed and used for specific purposes (Wyszecki and Stiles, 1982, p. 23). Those belonging to the first group are based on the principles of additive color mixture and colored light stimuli. The Ridgway Color System and Ostwald Color System are examples of the first group. The second group of color-order systems uses the principles of pigment mixtures, also known as subtractive color mixture. In this system, mixing limited numbers of pigments of paints in specific ratios creates the colored objects. Plochere Color System and Martin-Senour Hue System are the well-known examples of this group. The final group is based on the principles of color perception mechanisms of human eye and they are considered as “color appearance systems”. Major examples are Munsell Color System, Natural Color System (NCS), DIN Color System, Pantone Color System, and OSA Color System.

In buildings, DALI systems can be designed as a stand-alone system, stand-alone subsystem, or pure subsystem within building management. Each system has its own specific aim and technology that were outside the scope of this study.

Since the 1980s, departing from these requirements, modern buildings were equipped with digital systems. In the whole building, they enable the control and consumption of all lighting installations from one center. Although the idea of “central control” sounds simple, it requires advanced skills of both the lighting engineers who design it and workers who construct it. Due to this complex problem, an easy-to-use system was developed by a group of companies: DALI-AG (DALI, 2005).

DALI is an acronym that stands for “Digital Addressable Lighting Interface” and its aim is to create a simple interface for the designers and users for controlling complex situations. DALI is an international standard and guarantees the compatibility of dimmable ballasts from different manufacturers. Table 2.3 shows why DALI systems are widely used in modern buildings.

Table 2.3 The Advantages of DALI

Simple wiring of control lines (no group formation, no polarity)
Control of individual units (individual addressing) or groups (group addressing) is possible
A simultaneous control of all units is possible at any time (built-in initial operation function) through broadcast addressing
No interface of data communication is to be expected due to the simple data structure
Control device status messages (lamp fault)
Automatic search for control devices
Simple formation of groups through "flashing" lamps
Automatic and simultaneous dimming of all units when selecting a scene
Logarithmic dimming behavior - matching the sensitivity of the eye
System with assigned intelligence (individual address, group assignment, lighting scene values, fading time)
Operational tolerances of lamps can be stored as default values (for energy savings, maximum values can be set)
Fading: adjustment and dimming speed
Identification of unit type
Options for emergency lighting can be chosen
No need to switch on/off the external relay for the mains voltage
Lower system cost and more functions

Synchronization of LEDs

When three primary colors are combined, a measurable white light is obtained (Muthu, Schuurmans & Pashley, 2002). However, the LEDs could not be synchronized manually. The sensitivity of manual dimmers is not adequate for a scientific study. On the other hand, for a replicable experiment, the dimming ratios should be measurable and should be given for each white light with their specific intensities. For this purpose, in this study a digital dimming control system is used.

Digital Addressable Lighting Interface (DALI) Control Systems for LEDs

Williams (2005) describes the importance of light for mankind as follows:

> "The flaming touch and the campfire probably constituted the first use of 'artificial' lighting of the early man. For the first time, man gained some small degree of freedom from the blindness of night, and some small degree of safety from the fear of unseen prowling beasts. As early as 400,000 BC, fire was kindled in the caves of Peking man" ("Fire, Flame and Torch" section, para. 2).

From the first light of a torch, to the invention of new technologies like LEDs, humankind always searched for new ways of having light in their living environments. In modern times, the objectives of lighting changed from just illuminating the space or task to a more sophisticated level. Current lighting applications require convenient, functional, energy conservative, and other attractive features.

of the light source and object were calibrated to give a much better viewing condition.

2.4.2. COMPUTER-AIDED MUSEUM LIGHTING AND LEDS

Intelligent lighting systems were being used in museum lighting for decades. From the conservation point of view, it is recommended to install occupancy sensors in exhibition halls. When the visitors enter to a specific area, the lights are turned on and they view the objects. When they exit, the lights are turned off. By this method, the damage of the light sources will be minimized. Occupancy sensors regulate the operation of the light sources, as well as preserve the objects and decrease the cost for lighting.

Since LEDs do not emit unwanted radiations that damage the light-sensitive museum objects, an occupancy sensor will not be necessary for an LED based lighting scheme.

In this dissertation, a new lighting method was proposed that uses a computerized technology. The selection, creation, and control of the light source for the lighting of museum objects were conducted by computer-aided technologies. Additionally, computer software and digital measurement devices conduct digital control and creation processes of creating the white light.

contrary, the maintenance of a fiber optic system is not so easy and the initial cost is not so low. The bundles of fibers in the recessed ceilings or in the display cabinets are causing problems for the museum staff. In addition to these disadvantages, wavelengths below 400nm cannot be transferred through the fibers. Although this enables the filtering of ultraviolet, some region of the blue-violet light emission is also filtered. LEDs, that are compact and flexible, do not emit ultraviolet or infrared and they can replace the fiber optics in museum lighting.

LEDs have important advantages for museum lighting scheme. They have long lifetimes up to 100.000 hours, compared to other light sources such as fluorescent lamps with a maximum 20.000 hours of lifetime or incandescent lamps with an approximate lifetime of 8.000 hours. Their low operating costs, ruggedness, environmental friendliness, compact size, low operating voltages, and cold operation temperatures are the other advantages of LEDs. The power savings offered by modern LED lighting systems should be reason enough to consider them over other types of lighting designs (Dikel &Yener, 2007).

In addition to those advantages, LEDs were preferred especially to create a controlled white light that was specifically designed for the surface properties of the objects (Steigerwald, 2002). The aim of using LEDs in this study was to increase the quality of illumination of the object and enhance the viewing experience of the visitors. In this dissertation, in addition to the above, the CC

(1999) emphasize that, to justify their selection, their higher initial costs are compensated by a combination of benefits such as energy savings over the switching speed, ruggedness, and long operating life (p. 350).

Like every new and developing technology, LEDs, with their relatively low illuminance levels compared to florescent bulbs, need improvement for usage in general illumination. As Spagnoli (2002) states, LED manufacturers have made significant progress in solving the technical issues surrounding the use of white LEDs for general illumination applications.

Due to several advantages, discussed in the later parts of the study, LED technology has been penetrating museum lighting for a couple of years.

2.4.1. LEDS IN MUSEUM LIGHTING

According to the Philips Lighting Manual (1993), the lighting installation for a museum or art gallery should be capable of producing all the lighting effects appropriate to the character of the objects exhibited, whilst fully demonstrating the original intentions of the artist or exhibitor (p. 12).
In museum lighting, current practice uses fiber optic for light transmission. Since fiber optic is a light transmittance medium, it does not emit light. Generally, light sources with ultraviolet or infrared emissions such as incandescent halogens or metal halide light sources are preferred for fiber optic systems. Fiber optic technology is advantageous for museum lighting because they do not transmit infrared or ultraviolet wavelengths. On the

LED technology is being researched and developed by laboratories all over the world. Researchers in the Sandia National Laboratories focus attention on the passage of light sources in human history from fire to lantern, from bulbs to LEDs. They believed that this new white light source would change the way we live and the way we consume energy (Gee, 2002).

"In some ways the revolution in lighting can be compared to the revolution in electronics that began 50 years ago and is only now reaching maturity," Gee (2002, para. 4) states, "just as for electronics, glass bulbs and vacuum tubes are giving way to semiconductors and as in the microelectronics revolution, many of the possible applications for solid-state lighting will occur in ways that have not yet been envisioned".

The Economist underlines the gradual penetration of LED technologies into our daily lives. On their web page, this new light source was compared with other common light sources and they pointed out that "the light bulb is dead and that the days of the fluorescent tube are numbered". They predict that the future will be illuminated by LEDs ("A Solid Future," 2001).

As Sandia National Laboratories indicate, LED based light sources are currently expensive. They are more expensive than commercial incandescent light bulbs and they will not be practical until their cost is reduced and efficiency is further increased ("Quiet Revolution," 2002). However, like any relative immature technology, in the early years LED applications will be more expensive than incandescent solutions. Haitz, Kish, Tsao, and Nelson

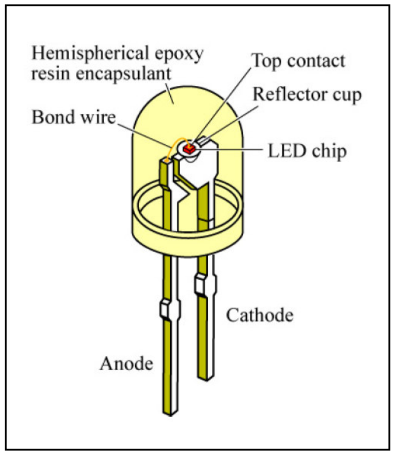


Figure 2.10. A Conventional LED.

The complex composition of semiconductors and the improvements in the design of LED chips require a different encapsulant. The new generation illuminator LEDs have much more light output than their indicator ancestors. This improvement was achieved by the complexity of the semiconductor compositions in PN junctions. They become more complex to emit more light.

PowerLEDs is a general name that represents the LEDs, designed for illumination, and a schematic drawing is shown in Figure 2.11. In addition, the design of the epoxy encapsulant is changed from dome shape to a more planar form, to give a wider light-emitting angle for general illumination purposes.

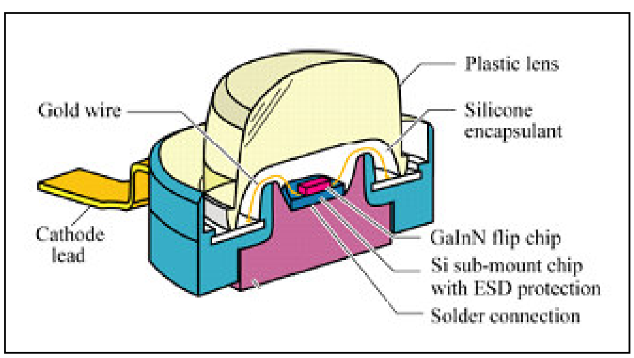


Figure 2.11. A PowerLED.

semiconducting element that forms the PN junction, electrons move from N area towards P area and holes move from P area towards the N area. At the junction, the electrons and holes combine: as this occurs, energy is released in the form of light that is emitted by the LED. Figure 2.9 shows the simplified PN junction diagram.

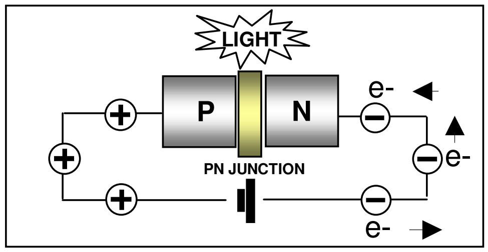


Figure 2.9. A Schematic Drawing of an LED.

The color of the LED is determined by the semiconducting element. Bullough (2003) conducted several experiments on the elements of semiconductors and he defined the two main types of elements presently used for lighting systems as aluminum gallium indium phosphide (AlGaInP), alloys for red, orange and yellow LEDs; and indium gallium nitride (InGaN), alloys for green, blue and white LEDs (p. 5). The slight changes in the composition of these semiconductor results in the changes of the color of the light, emitted by the LEDs.

The early LEDs that were used as indicators had an epoxy encapsulant over the light-emitting chip. This epoxy encapsulant around the chip decreased the unwanted scattering of the light and allowed light to be sent to a desired area with a required angle. These encapsulants had rectangular or round shapes. In Figure 2.10, an LED, typically used for indication, is shown.

past decade, as Bullough (2003) states, "LEDs had sufficient intensity for use in more than a handful lighting applications and specifiers are confronted with an increasing number of lighting products that incorporate LEDs for special applications" (p. 3). Bierman (1998) explains this rapid penetration of LEDs into the market due to the improved production processes by using new semiconducting materials. He also pointed out the fact that, current generation of bright LEDs has luminous efficacies[6] greater than incandescent lamps. For comparison, a traditional 40-Watt tungsten incandescent bulb has a luminous efficacy of approximately 14 lumen per Watt (Osram, n.d.), whereas the new LEDs have 70 lumen per Watt efficacies (Cree, n.d.).

Early LEDs with very low light emissions were used in electronic equipments as an indicator, for a couple of decades. However, due to several ameliorations of its chemical components and the demand for energy efficient light sources, LEDs began to be used as light sources for general and task lighting applications (Narukawa & Mukai, 2003). To suggest LEDs as suitable light sources for museum lighting, their structure, light-emitting principles, and advantages have to be explained briefly, initially.

An LED is a semiconductor device that emits visible light when an electric current passes through two different chemical materials. The area where these two materials come together is called the PN junction. The P side contains excess positive charge with holes[7], while the N side contains excess negative charge, the electrons. When a voltage is applied to the

[6] Luminous efficacy of a light source is the quotient of the luminous flux emmitted by the power consumed (CIE 38).
[7] In solid state physics, an electron hole (usually referred to simply as a hole) is the absence of an electron.

they normally presuppose some rules-of-thumb, such as producing tension and drama with high contrast of light and color and creating a mood of relaxation with overall soft lighting and pastel colors (Kesner, 1993, p. 46). Some major factors such as conservation and codes limit their creativity and as the National Center for Preservation Technology and Training Committee (NCPTTC) (1999) states, they continue to face challenges of caring for collections with appropriate conservation practices while providing visitors with quality viewing experiences (p. 3). The general atmosphere of the exhibition can be planned, created, and controlled by the curators. Strict rules or codes cannot standardize these intuitively designed settings. However, the photometric properties of light sources have to be chosen by certain rules or at least rely on a technically created basis, to conserve the objects and improve the visual performance of the visitors (Çığırgan, 1995,)

In countries where both conservation and effective perception of museum objects is important, museum lighting becomes more complicated. In the Museum Lighting Protocol, published by the NCPTTC (1999), curators and exhibit designers are required to consider factors such as visual perception, Color Temperature, and different types of artificial illumination as part of the overall lighting equation (p. 1).

2.4. LIGHT EMITTING DIODES

LEDs were first introduced to market in the early 1960s, and their low illuminance levels were limiting their usage as miniature indicators. In the

CRI and CCT are the two major issues that guide lighting designers and curators in museums. Institution and commissions have carefully established guidelines for these two factors of light sources.

The next section introduces the third often-overlooked property of light sources: the Chromaticity Coordinates.

2.2.3. CHROMATICITY COORDINATES

The Chromaticity Coordinates of an object is a measurable value. The perceived warmth, hue, and saturation are dimensions of color vision that can be related directly to spectrally opponent mechanisms in the human visual system. The CC of an object is used frequently in industry, where a precise color description is essential. For instance, when a company designs a device and wants to have a patent for their product, the technical descriptions, the design, and the function of the product can be described by technical drawings and verbal descriptions. However, the color of the device can only be described and patented by defining its Chromaticity Coordinates under a reference light source, like the famous yellow film box of Kodak photograph company (Kaiser, 1996).

2.3. CURRENT LIGHTING METHODOLOGY IN MUSEUMS

In most museums, curators set the gallery illumination schemes (IES, 1996, p. 12). Their judgment is guided generally by experience and intuition and increased, the preference field of the Color Temperature becomes broader and shifts to Color Temperatures with higher Kelvin values.

Although in many sources, this “canonical” curve is appreciated, Davis and Ginthner (1993) point out that, “the curve defining the lower Color Temperature limit at each intensity was simply determined by the lamps available to him at that time” (p. 48). The lighting technology in 1941 was limited when compared to the current light sources. On the other hand, Scuello et al. (2004) give emphasis to the narrow scope of the works of Kruithof, as he did not concentrated directly on museums or aesthetics; “he simply claimed to specify optimal illumination in the workspace, assuming that something neither warm nor cool was best” (p. 308). Scuello et al (2003), in their article about museum lighting, argue that Kruithof worked with preference of the people in illuminating a room successfully; he did not deal specifically with viewing art or consider some basic factors like color discrimination or color appearance (p. 22).

When designing a lighting scheme in a museum, the Kruithof Curve and other regulations by ICOM or other institutions should not be the sole consideration. Regulations should be implemented relative to the particular conditions or objects, since any museum object requires a unique lighting solution.

Relation between the wavelength and Color Temperature is explained as the protection of object from damage. On the other hand, the “illuminance-Color Temperature relation based practice” is relying on a highly cited work done by A. A. Kruithof in 1941 (p. 64).

Scuello et al. (2004) find museum lighting as an intuition based practice and they stress the fact that there is insufficient research that takes into account the constraints imposed by the human visual system when viewing art works. They reveal the fact that much of the research was concentrated on creating pleasing illumination and this is the tradition that has provided the canonical set of data for museum settings, known as the “Kruithof Curves” (p.123) (Figure 2.8).

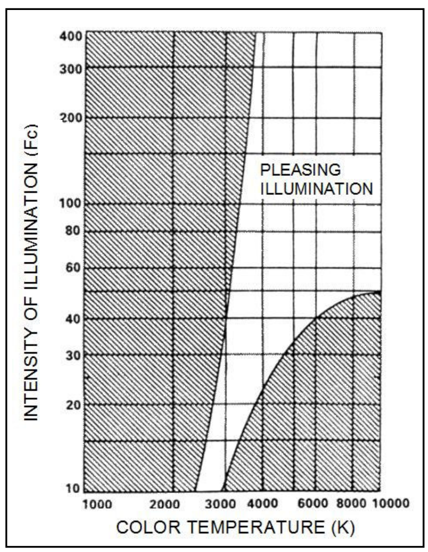


Figure 2.8. The Kruithof Curve.

According to Kruithof, as seen in Figure 2.8, the light sources with low Color Temperature are preferred at low illuminance. When the intensity is

Table 2.2. Group of Materials and Color Temperature Recommendations of ICOM.

		CCT
Group 1	**Extremely Sensitive Objects** Organic based materials, textile, carpet, leather, watercolor, ...	2900 K
Group 2	**Sensitive Objects** Oil paintings, varnished furniture pieces, ...	4000 K
Group 3	**Insensitive Objects** Stone, Metal, Glass, Earthenware, …	3000-6500 K

As seen in Table 2.2, each group in the classification of ICOM requires a different Color Temperature. The illuminance, as discussed earlier, becomes lower when the object is sensitive to light-based damages. The Color Temperature, similar to illuminance, decreases when the sensitivity of the object increases. The reason being: a light source with a Color Temperature of 2900 Kelvin emits a light with a dominant wavelength of approximately 500nm. This is the region where blue light ends and green light begins. In Figure 2.7, the damage amounts of wavelengths are plotted on a graph. Note, at nearly 500nm, damage from the light source is minimized.

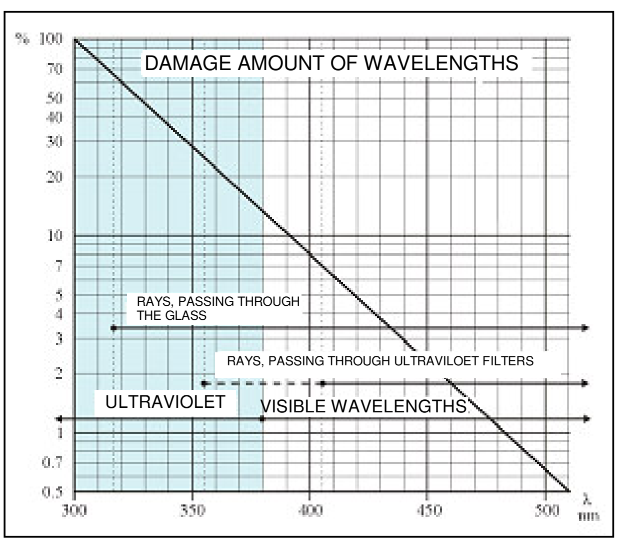


Figure 2.7. Damage Amounts of Wavelengths

method of calculating the Correlated Color Temperature of a stimulus as “to determine on a Chromaticity Diagram the temperature corresponding to the point on the Planckian Locus[5] that is intersected by the agreed isotemperature line containing the point representing the stimulus” (p. 452). In Figure 2.6, the curved line represents the Planckian Locus and the numbers on the line are the Color Temperatures plotted on the 1931 CIE Chromaticity Diagram. The close-up represents the Correlated Color Temperature line. Note that Point A on Planckian Locus is a light source with a Color Temperature of 5000K and Point B is another light source with a Correlated Color Temperature of 5000K.

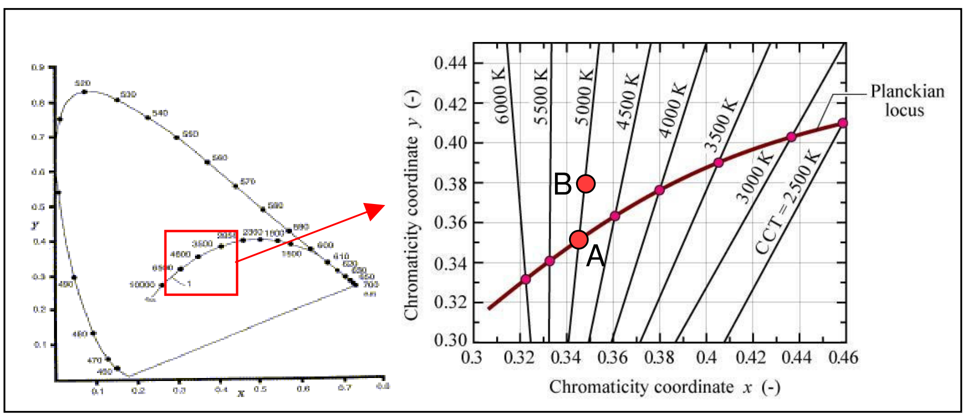


Figure 2.6. The 1931 CIE Chromaticity Diagram, Planckian Locus and a Close-up View of the Locus, Showing the CCT Lines.
http://www.ecse.rpi.edu/schubert/Light-Emitting-Diodes-dot-org/chap18/chap18.htm

According to ICOM (1953), in museums there are strict regulations about the Color Temperatures of the light sources (p. 14). ICOM divides the museum objects into three categories: extremely sensitive, sensitive, and insensitive objects (Table 2.2).

[5] Planckian Locus is a line in chromaticity diagram representing full radiators of different temperatures (CIE 73).

IESNA (2000) declares the minimum CRI values for museums and art galleries as 85 (p. 79). As indicated earlier, Color Rendering Index of a light source cannot be considered without its Correlated Color Temperature. For this reason, these two factors should be considered concurrently while designing a lighting scheme,

2.2.2. COLOR TEMPERATURE

Color Temperature refers to “a way of describing the chromaticity of a particular category of white light in terms of the chromaticity of the light emitted by a theoretical black body radiator at a certain temperature” (Kerr, 2006, p.1). For instance, A 3000 Kelvin (K) refers to a light source with dominant red and orange wavelengths in its spectral distribution, whereas an 8000 or higher Kelvin source is a blue dominant light source (Figure 2.5).

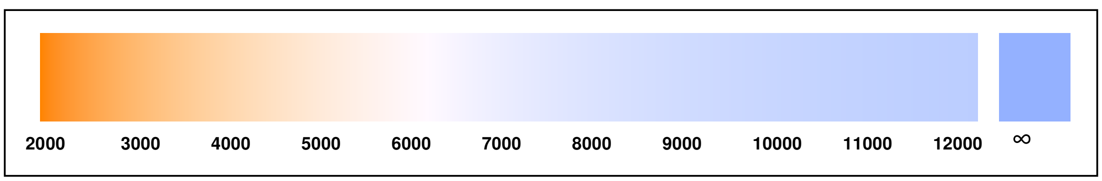
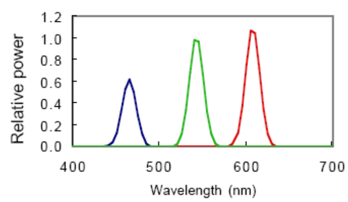


Figure 2.5. Schematic Description of Color Temperature and its Appearance.

The concept of Correlated Color Temperature, as Borbely, Samson, and Schanda (2001) state, is somewhat more complicated, since it has both perception-based and psychophysical definitions (p. 450). It is the temperature of the Planckian Radiator whose perceived color mostly resembles that of a given stimulus, at the same brightness, and under specified viewing conditions. Borbely et al. (2001) explain the recommended

Color Temperature” (p. 5). They admit that it is not necessary to match the spectral power distribution of a black body to achieve a high CRI value. An alternative method of obtaining a high CRI value is the use of tri-phosphor fluorescent lamps. Thornton (1992) describes this method as “the combination of wavelengths with a band center of approximately 450nm, 530nm and 610nm, that have the characteristic colors of blue, green, and red, respectively” (p. 85). Figure 2.4 shows the spectral distribution of an LED source with three dominant wavelengths, their Chromaticity Coordinates, and other photometric data.



CRI (Ra)	80
CCT (K)	4011
x	0.3812
y	0.3795
Efficacy (Lm/W)	399

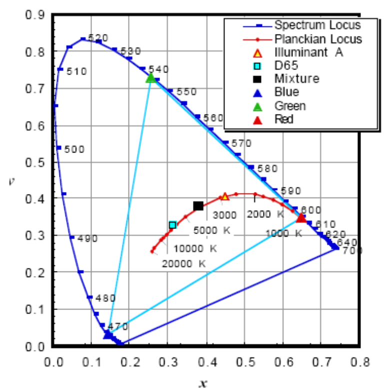


Figure 2.4. Simulation of a Three-chip White LED.

As seen in Figure 2.4, the spectral distribution graph shows three peek points at certain dominant wavelengths. The Color Rendering Index and other parameters of the white light are listed. On the right side of the figure, the white light, obtained from the mixture of red, green and blue wavelengths, represented as a black square box that is plotted on the CIE Chromaticity Diagram.

Figure 2.2. Effects of Two Separate Lamps Having Identical CRI Values, but Different Chromaticity Coordinates.
http://www.donsbulbs.com/bulbs/g/glossary/cri.example7.jpg

Low CRI values are acceptable for the illumination of highways, parking lots, or tunnels. However, in museums and art galleries, where the primary aim is the right perception of colors by the visitors, a high CRI value is required. The effects of different CRI values on the same object are shown in Figure 2.3. The same flower arrangements illuminated with sources having CRI values of 50, 70, and 100 appear different. Under CRI value of 100, the colors of the flowers are more vivid than the others, under lights of lower CRI values.

Figure 2.3. Effects of Light Sources with Different CRI Values on a Flower Arrangement.
http://www.donsbulbs.com/bulbs/g/glossary/cri.examples.jpg

The CRI value of an incandescent lamp is nearly 100. This good color rendering property is related directly to the structure of the black body[4]. Black body radiators, as scientists in Lighting Research Center (1998) report, "are perfect only if the color appearances of illuminated surfaces match the appearances that they would have, if illuminated by a black body of the same

[4] Black body, also known as the Planckian Radiator, is a thermal radiator, which emits completely all-incident radiation, whatever the wavelength, the direction of incidence, or the polarization. This radiator has, for any wavelength, the maximum spectral concentration of radiant existence at a given temperature (CIE, 1970, p. 24).

The present study aimed to propose an LED-based method for museum lighting, in which the harmful wavelength emissions of the light source are avoided.

2.2. PHYSICAL COMPONENTS OF LIGHT

Color Rendering Index, Color Temperature, and Chromaticity Coordinates are three physical and measurable components of every light sources.

2.2.1. COLOR RENDERING INDEX

In general terms, as Egan and Olgyay (2002) explain, the Color Rendering Index is a number obtained by comparing light sources to a standard reference source by measuring color shifts on eight color test samples (p. 388). A light with high CRI makes colors look natural and vibrant, low CRI causes some colors to appear dull or even have a different hue. The CRI value of a light source can be on a scale between 0 and 100. On this scale, a CRI of 100 would signify that the eight color samples illuminated by a light source appear the same as when illuminated by the reference source. CRI is not an exact number, and poor performance with one color may be compensated by a better performance with another color. Therefore, two lamps having identical CRI values can have varying color-rendering abilities (Figure 2.2). To compare lamps, they must have identical Chromaticity or Color Temperature.

IESNA (2000) describes the negative effect of light on museum objects as follows:

> Light is a radiant energy and exposure to light gradually causes permanent damage to many museum objects. When radiant energy is incident on the surface of a material, whether opaque or transparent, some portion of that energy is absorbed. This can promote two distinctly different processes that can cause degradation of museum objects: photochemical action and radiant heating (p. 14).

Ultraviolet and Infrared are the two harmful wavelengths in lighting issues. Ultraviolet is the region of wavelengths below 380 nm. An object, exposed to ultraviolet radiation, will have a photochemical reaction and its color will degrade by time. Organic-based objects, like textile and paint pigments, are very sensitive to these kinds of rays. The second harmful radiation is infrared, with wavelengths above 780 nm. The negative outcome of infrared wavelengths is heat and by unbalancing the humidity level of the art object with its environment, it causes serious damage. The rapid changes in the surface temperature results in minor or major cracks. Infrared wavelengths also increase the speed of endothermic reactions, as well as occurrence of expansion between the two surfaces that are chemically and physically different from each other by color, texture, and material. In Figure 2.1, the ultraviolet and infrared regions are plotted on a spectral graph.

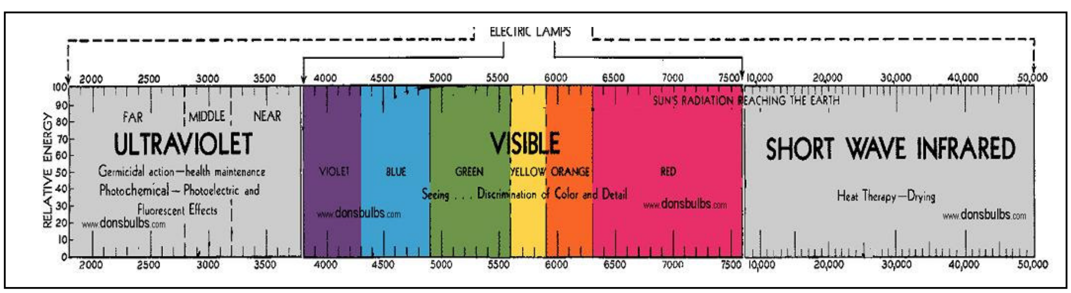


Figure 2.1. The Ultraviolet and Infrared Regions.
http://www.donsbulbs.com/bulbs/g/l/ge1956lampbulletin/38.39.gif

2.1.2. HARMFUL WAVELENGTHS

Scuello, et al. (2004) express the fact that, “most papers on museum lighting acknowledge the emphasis on the importance of conservation, rather than satisfying the viewing public” (p. 309). Light is an effective tool in a museum environment, where the primary aim is to exhibit cultural heritage to public view, since Druzik (2004) points out that the last half of the 20th century saw the widespread acceptance and application of environmental guidelines to protect museum collections.

The light source in a museum, as IESNA (2000) states, should be selected carefully, since lighting can cause or accelerate degradation of certain kinds of museum objects (p. 7-34). The lighting scheme in museums and art galleries differs in some important aspects from many other types of lighting design: many museum objects, often unique in size, shape, texture, and color, are extremely sensitive to damages from improper light sources. A variety of codes and regulations limit the exposure time of the specially selected or carefully filtered light sources to prevent any possible damages. In the case of damage of museum objects under light, as IES Lighting Handbook (1987) states, there is a direct relation between the illuminance level and exposure time (p. 19-32). While limiting the exposure time and level, there must be sufficient illuminance on objects, to make them visible to all visitors. Current lighting in museums has problems due to the limitations of the quantity of light, without considering the quality of light.

from the surface. This decreases the luminance contrast depending on the roughness of the surface” (p. 20).

After conducting numerous experiments on color discrimination and detail acuity, Boyce (1987) concludes that there is no exact illuminance level in an art gallery or museum (p. 55). According to the author, the illuminance will depend on the size, contrast, reflectance, and colors of the object. In his study, he also showed that due to the physiological defects in their vision mechanisms, elderly visitors have problems with relatively low illuminance levels, and they require more illuminance on objects for successful color discrimination.

Although there are general rules for illuminance levels in museum lighting, they are just guidelines for the curators or lighting designers (Dean, 1994, p.18). Each art object has unique size, color, shape, texture, and material. The successful approach for designing the lighting scheme should be based on a method that departs from those tabular guidelines and be modified according to the object and the profile of the visitors. The limited exposure times and low illuminance levels are established by considering the ordinary light sources. The guidelines can be revised for the benefit of all sections of the museum visitors by using new light sources, technologies, and methods.

2.1.1. ILLUMINANCE

Conditions of illuminance in home, office, and other indoor places are well established in codes, regulations and publications of institutes like the Chartered Institution of Building Services Engineers (CIBSE), International Commission on Illumination (CIE)[2] or IESNA. In these reference sources, recommended intensities in museum lighting are typically low, to prevent damage. The reason for low intensities is “the general practice of using readily available artificial light sources in museums, that carries UV or IR in their spectral structure” (Scuello, Abramov, Gordon, & Weintraub, 2004, p.121). In Table 2.1, the recommended illuminance and durations for museum lighting are listed (IESNA, 2000, p. 14-4). These levels and exposure durations are strictly regulated by those codes.

Table 2.1. Illuminance in Museums

Types of Materials	Maximum Illuminance	Hours Per Year
Highly susceptible displayed materials: Textiles, cotton, natural fibers, furs, silk, writing inks, paper documents, fugitive dyes, watercolors, wool, some mineral	50 lux[3]	50.000
Moderately susceptible displayed materials: Textiles with stable dyes, oil paintings, wood finishes, leather, some plastics	200 lux	480.000
Least susceptible displayed materials: Metal, stone, glass, ceramic, most minerals	Depends on the exhibition situation	

Robilotto and Zaidi (2006) suggest that a change in the illuminance effects the perception negatively. They emphasize the fact that “increasing the incident light to increase the mean luminance, increases the scattered light

[2] Abbreviated as CIE from its French title - Commission Internationale de l'Eclairage.
[3] 50 lux is considered as the lowest practical level for exhibits for which color discrimination is an important factor.

2. LIGHTING OF MUSEUM OBJECTS

Literature about museum lighting studies and applications concerning the photometric properties of light sources and their relationship with museum objects are the focus of this chapter.

2.1. STANDARDS FOR MUSEUM LIGHTING

A widely accepted definition of a museum is as follows: “An organized and permanent non-profit institution, essentially educational or aesthetic in purpose, with professional staff, that owns and utilizes tangible objects, cares for them and exhibits them to the public on a regular schedule” (IES, 1996, p. 7-34). In this definition, the museum is an organization with certain aims and methods that mainly concentrate on the objects. However, the function, technique, and quality of exhibiting the tangible objects to the public should be considered skillfully because a museum is foremost a place for the public.

Illuminating Engineering Society of North America (IESNA) defines the highest responsibility of a museum as the study and care of its collection and to provide an effective public display of them (IESNA, 2000, p. 7-33). Such effectiveness can be achieved by means of careful selection and appropriate use of light sources.

The fourth chapter introduces the materials on which the study was conducted. Here objects and their colors, the subjects, the experimental setup, and the control equipments together with the properties of LEDs are described. The fourth chapter describes the procedure of how the materials come together in an experimental setup.

The results of the evaluation of each attribute and their statistical analysis are the subject of the fifth chapter. The validity of the method and its further application areas are discussed in the next two chapters.

adapted to digital control systems. A common method of obtaining white light in LED industry, the Red-Green-Blue (RGB) technique, is proposed to create an LED with the desired CC value. White lights with the desired CC value are achieved by adjusting the illuminance levels of red, green, and blue LEDs, by computerized techniques in laboratory conditions.

An experiment was conducted to test this method. First, by considering certain criteria, surface colors and the samples were chosen. They were then illuminated with special RGB LED sources having the same CC with the objects. Three other LED sources representing common light sources in the market with CCT of 3000, 4200, and 6500 Kelvin and a D65 reference light source were used for the visual comparison of the subjects. The validity of the findings was tested by statistical analysis methods.

This dissertation consists of seven chapters, including this introduction, where its argument, objectives, and procedure are given.

The second chapter contains a literature survey on museum lighting, the usage of photometric properties of light sources in museum lighting applications and LEDs.

The third chapter briefly explains the color-order systems and the effect of light on three major attributes of visual sensation: hue, saturation, and brightness.

b. The Correlated Color Temperature (CCT) of the source should be considered prudently.
c. The Color Rendering Index (CRI) properties should reinforce the appearance of the object on display.

Apart from the factors listed above, there is another important physical aspect of light sources: their Chromaticity Coordinates (CC) (Scuello, Abramov, Gordon & Weintraub, 2004). In the publications of well known institutions such as the International Council of Museums (ICOM) and Illuminating Engineering Society of North America (IESNA), recommended values for CCT and CRI are given as conservation requirements[1]. However, there is no definite information about the use of CC of the light sources in museum lighting installations.

Departing from this ongoing need, this dissertation aims to find a method for choosing the light source that is based on the CC of the surface properties of the object. This method was intended to enhance the visual experience of museum visitors by illuminating the museum object with a created light source, having the same CC with the object. It is assumed that by bridging the gap between the photometric properties of light sources and surface properties of the objects, perception of the art objects would be improved.

Light Emitting Diodes (LEDs) were proposed as the light sources. They satisfied the first selection factor: they did not contain UV and IR portion of the radiation spectrum in their spectral distribution, and they can easily be

[1] These issues will be discussed in Chapter 2.1.1.

1. INTRODUCTION

Light is a crucial factor for viewing an object. Without light, a person can see neither the color and texture, nor significant details of an object. In lighting installations where the primary aim is to illuminate the object effectively, quality, quantity, and location of the light sources become important issues. The object, displayed for public view, can be a collection of automobiles in a gallery, fish on display in a market or a unique ethnographic object in a museum.

Museum lighting should concurrently should satisfy both the needs of visitors and the conservation requirements of the artifacts. There must be a balance between these two needs in order to advance the museum experience. In recent decades, lighting designers have been selecting light sources that do not carry harmful wavelengths, due to a higher level of conservation consciousness. However, the visitors are not observing this sensitive approach in the case of enriching perception of the objects.

In museum lighting, the following three factors have to be considered, while deciding on the light sources (IES, 1996):

a. A chosen light source should not carry harmful wavelengths; namely, infrared (IR) and ultraviolet (UV).

LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

I would like to thank Assoc. Prof. Cengiz YENER, for his patience and guidance throughout the many phases of this dissertation.

I am also grateful to the jury members, for their guidance and valuable comments.

I would like to thank the Interior Architecture and Environment Design Department of Bilkent University, for the financial support of D65 and the experiment boxes.

My special thanks go to the students of Interior Architecture and Environmental Design Department of Bilkent University.

Osram and Tridonic-Atco, two major LED-manufacturing companies, sponsored our study. I would like to thank Mr. Holger KRAUS from Osram and Necdet KINALI from Tridonic-Atco for their valuable support on the LED modules and DALI systems.

I am thankful to Mr. Selçuk ÖGER, the representative of Datacolor in Turkey, for his assistance with the Spectrophotometric measurements and access to the D65 reference illuminant.

I will never forget the last minute support of my colleague, Mr. Ralph PRIDMORE of Macquarie University, Australia.

Without the existence, encouragement and patience of my wife, Simge ŞENGÜN DİKEL, this dissertation would not have been prepared in contented conditions.

This Dissertation is dedicated to my source of inspiration, Berna-Orhan DİKEL, Hayat-İlhan ŞENGÜN.

ÖZET

NESNE AYDINLATILMASINDA YENİ BİR YÖNTEM

YÜZEY KROMATİSİTE KOORDİNATLARININ LED TABANLI AYDINLATILMA ARACI OLARAK MÜZELERDE KULLANIMI

Ekrem Erhan DİKEL
Güzel Sanatlar, Tasarım ve Mimarlık Fakültesi Doktora
Tez Yöneticisi: Doç. Dr. Cengiz YENER
Eylül, 2007

Günümüz çağdaş müze aydınlatılmasında uygun renksel geriverim ve renk sıcaklığı değerlerine sahip, aynı zamanda tayfsal dağılımında kızıl üstü ve mor altı dalga boyları içermeyen ışık kaynağı seçilmektedir. Ancak ışık kaynaklarının genellikle göz ardı edilen bir diğer önemli özelliği olan kromatisite koordinatları hiçbir tabloda yol gösterici olarak ışık tasarımcısı ya da küratörlerin kullanımına açılmamıştır. Bu çalışma, eserlerin yüzey renklerinin kromatisite koordinatları ile, seçilecek ışık kaynağının kromatisite koordinatları arasında bir ilişkilendirme kurmayı ve gelecekteki müze aydınlatmalarında yol gösterici bir yöntem oluşturmayı hedeflemektedir. Bunun için, geleceğin ışık kaynağı gözüyle bakılan Işık Yayan Diyot (Light Emitting Diode) LED teknolojisi incelenmiş, seçilen örneklerin aydınlatılmasında bilgisayar destekli aydınlatma yöntemleri kullanılarak bir deney düşünülmüştür. Çalışmada, renkli nesnelerin kromatisite koordinatlarına göre özel olarak üretilen ve aydınlatma uygulamalarında sıkça kullanılan 3000, 4200 ve 6500 Kelvin renk sıcaklığına sahip ışık kaynakları altındaki görünümleri referans ışık kaynağı olarak kabul edilen D65'in altındaki görünümleri ile kıyaslanmış ve deneklerden çeşitli değerlendirmeler yapmaları istenmiştir. Yapılan deneyin sonucunda; yüzey renkleriyle aynı kromatisite koordinatlarına sahip ışıkla aydınlatılan nesnelerin denekler tarafından daha çok tercih edildiği görülmüştür. Çalışma, çağdaş müzecilik uygulamalarında ışık kaynağı seçimine yönelik yol gösterme özelliği ile literatüre katkı sağlamaktadır.

Anahtar Sözcükler: Kromatisite Koordinatları, LED, Müze Aydınlatması

ABSTRACT

A NEW METHOD IN OBJECT LIGHTING

USING SURFACE CHROMATICITY COORDINATES AS A LED-BASED LIGHTING TOOL IN MUSEUMS

Ekrem Erhan DİKEL

Ph.D. in Art, Design, and Architecture

Supervisor: Assoc. Prof. Dr. Cengiz YENER

September, 2007

In contemporary museum lighting, the common practice is to choose light sources with recommended Color Rendering Indices (CRI) and Color Temperatures (CT) that do not emit harmful wavelengths: ultraviolet and infrared. In addition to CRI and CT, the commonly disregarded component of each light source, the Chromaticity Coordinates (CC), do not exist in any guidelines that are intended to be used by museum lighting designers and curators. This thesis aims to create a guideline for the museum lighting designers by proposing a new lighting method based on the relation between the surface CC of the museum objects and the CC of the light sources that are proposed to be their illuminators. For this reason, an experiment was conducted by using the Light-Emitting Diodes (LEDs) and computerized lighting controlled systems to test the validity of the proposed method. In the study, the appearances of the colored objects under a D65 reference light source were evaluated by comparing the created light source with their CC values and three other LED light sources with CT of 3000, 4200, and 6500 Kelvin that are mainly used in the museum lighting design applications. The results of the experiment showed that subjects preferred the appearance of the objects under lights that have same CC as the object. This thesis contributes to the museum lighting literature by creating the basis for a guideline for choosing and creating unique light sources for objects, by using their own physical properties.

Keywords: Chromaticity Coordinates, Light Emitting Diodes (LED), Museum Lighting

I certify that I have read this dissertation and that in my opinion it is fully adequate in scope and quality as a dissertation for the degree of Ph.D. in Art, Design and Architecture.

____

Assoc. Prof. Dr. Cengiz YENER (Principal Advisor)

I certify that I have read this dissertation and that in my opinion it is fully adequate in scope and quality as a dissertation for the degree of Ph.D. in Art, Design and Architecture.

Prof. Dr. Mustafa PULTAR

I certify that I have read this dissertation and that in my opinion it is fully adequate in scope and quality as a dissertation for the degree of Ph.D. in Art, Design and Architecture.

Assoc. Prof. Dr. Halime DEMİRKAN

I certify that I have read this dissertation and that in my opinion it is fully adequate in scope and quality as a dissertation for the degree of Ph.D. in Art, Design and Architecture.

Assist. Prof. Dr. Semiha YILMAZER

I certify that I have read this dissertation and that in my opinion it is fully adequate in scope and quality as a dissertation for the degree of Ph.D. in Art, Design and Architecture.

Assist. Prof. Dr. Cüneyt KURTAY

Approved by the Institute of Fine Arts

Prof. Dr. Bülent ÖZGÜÇ, Director of the Institute of Fine Arts

A NEW METHOD IN OBJECT LIGHTING

USING SURFACE CHROMATICITY COORDINATES

AS A LED-BASED LIGHTING TOOL

IN MUSEUMS

A DISSERTATION
SUBMITTED TO THE INSTITUTE OF FINE ARTS
OF BİLKENT UNIVERSITY
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY
IN ART, DESIGN AND ARCHITECTURE

By

Ekrem Erhan DİKEL
September, 2007