Virtual Reality as a Surrogate Sensory Environment for Evaluation of Human Luminous Environment

Mojtaba Navvab

The University of Michigan Ann Arbor MI 48109-2069,

Light is one of the most important factors in design of architectural space, enabling us to view the shape, color and movement of objects within our surroundings and enjoy the living environments through our eyes. Architectural lighting also impacts our well-being by evoking a variety of **"non-image-forming"** physiological responses, such as constriction of the pupil, synchronization of circadian rhythm, acute modulation of alertness, and regulation of hormone release. The latest design and fabrication of different types of LED - based light sources are exhibiting ability to control their lighting characteristics with various impacts on architectural spaces or luminous environment.

A "virtual reality" technique is used to test these lighting conditions while studying both **image-forming** and non-image-forming visual responses to these light stimuli. The focus has been primarily on the visual response of human subjects with normal vision under simulated environment. Combining different simulation techniques with an interactive **C**omputer **A**ssisted **V**irtual **E**nvironment "CAVE" in real-time can remarkably accelerate the decision-making process. A virtual reality environment produces sensory stimulation very close to reality.

Colour or its perception, is one measure or index by which to estimate the closeness of the sensations created with simulation techniques which demand a high degree of realism compared to the physical environment. Quality of Colour or their appearance, generated within a scene illuminated by the various CAVE projectors, is evaluated using the Colour Quality Scale Index. The Colour Rendering Index (CRI) using Munsell Color samples and the CIE LAB are used to examine the consistency of colour reproduction. The results show that the source spectral power distribution and the surface spectral reflectance are the key dimensions of the parameters that are most essential in providing a stimulus which produces a realistic colour appearance and a successful simulation of a distinct lighting condition within the virtual environment.

The UM 3D VR Laboratory includes an immersive virtual-reality CAVE-like environment, measuring 10 ft (3.048 m) in width, depth, and height. It runs on a cluster of six workstations, with one control computer, one motion-tracking computer, and four rendering computers. Four Christie Mirage S+4K projectors produce 3D images on the left, front, right, and floor surfaces. The system resolution per surface is 1024 x 1024 pixels. The stereo mode is frame-sequential (alternating left-right) at 96 frames per second. Infrared emitters synchronize Stereo Graphics Crystal Eyes® liquid crystal shutter glasses with the projectors. A Vicon MX13 system with eight 1.3 megapixel cameras provides wireless (near infrared) motion-tracking of the shutter glasses and a Logitech Rumble Pad game controller. The software is an ongoing in-house development, named Jugular, which integrates several open-sources, proprietary, and custom-developed subsystems for graphics, sound, animation, physics, motion-tracking, data management, and networking. Actual and schematic views of the CAVE's back screen projectors outputs and their locations are shown in **Figure 1.**

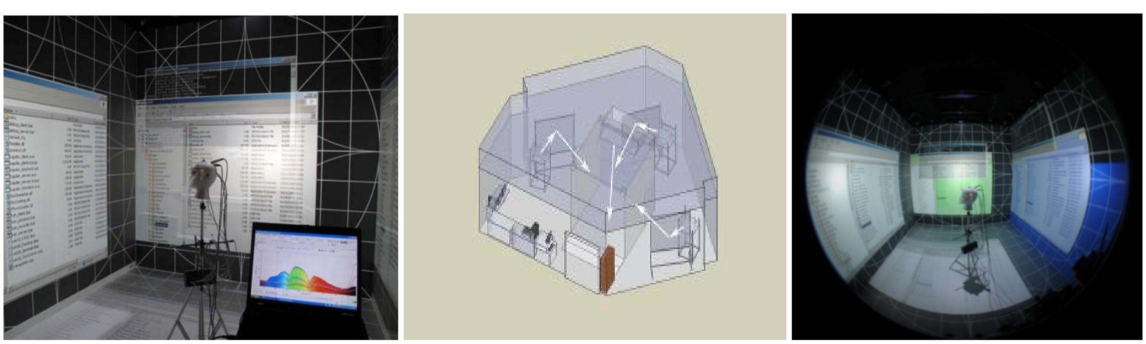


Figure 1, Real and schematic views of the CAVE's projectors outputs and their locations

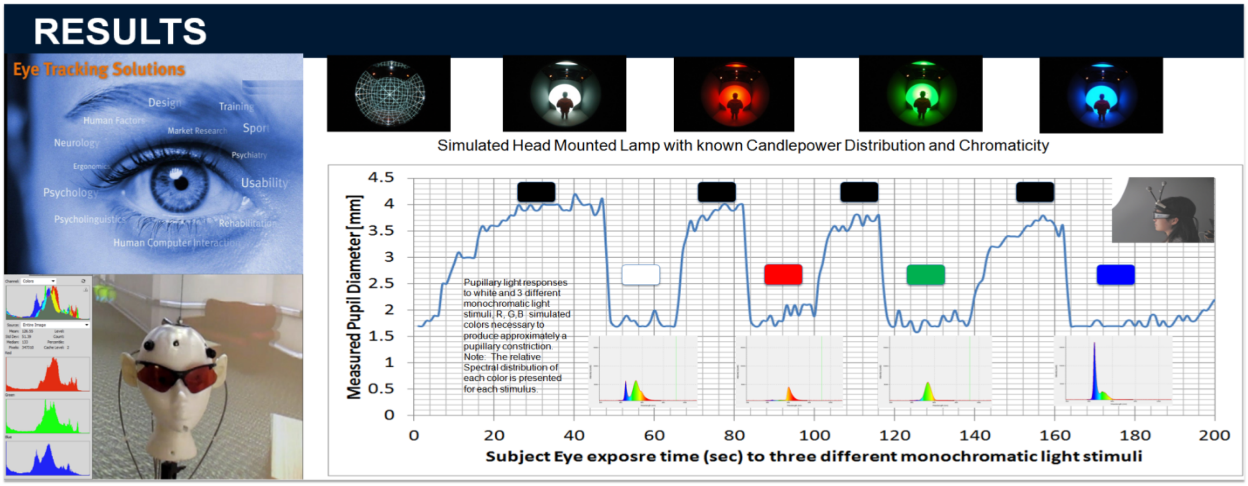


Figure 2, *Measuring RGB within a simulated scene is shown within an immersive Virtual Reality (VR) enclosure or Computer Assisted Virtual Environment (CAVE). The manikin head is fitted with spectrometers behind the 3D stereoscopic-glass to account for the glasses' absorption and tint while measuring the SPD for a given viewing direction in a simulated scene. Pupillary light responses to white and 3 different monochromatic light stimuli, R, G, B simulated colors necessary to produce approximately a pupillary size of constriction (mm) are measured. The relative spectral distribution of each color and changes in the pupil diameter are presented for each stimulus.*

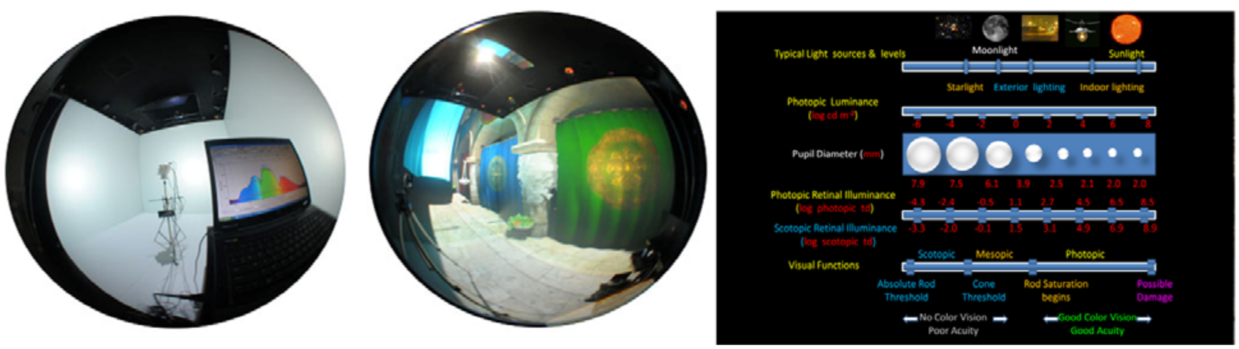


Figure 3, Left: *Simulated complex scene in the CAVE using dynamic range spectral distribution,* ***Right:*** *Illumination levels for typical ambient light levels are compared with photopic luminance (log cd/m^2), pupil diameter (mm), photopic and scotopic retinal illuminance (log photopic and scotopic trolands) respectively and visual function. The scotopic, mesopic and photopic regions are defined according to whether rods alone, rods and cones, or cones alone operate. The conversion from photopic to scotopic values assumed a white standard CIE D65 illumination (based on the design of Hood and Finkelstein, 1986).*

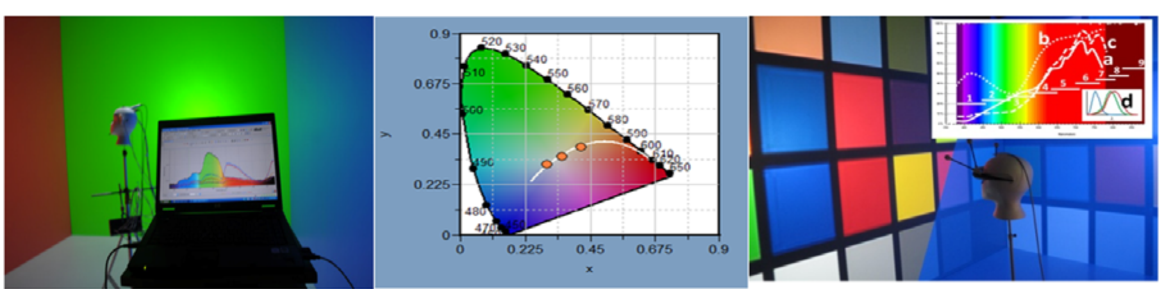
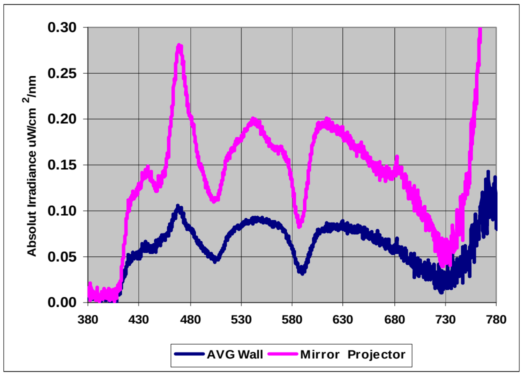


Figure 4, Left: *Simulated scenes within the CAVE using high dynamic range of visible light.* ***Center:*** *Measured data of simulated conditions plotted on the CIE 1931 x, y Chromaticity.* ***Right:*** *Macbeth color chart as a reference and blue glazing are simulated within the CAVE using the dynamic range of their spectral distribution.*



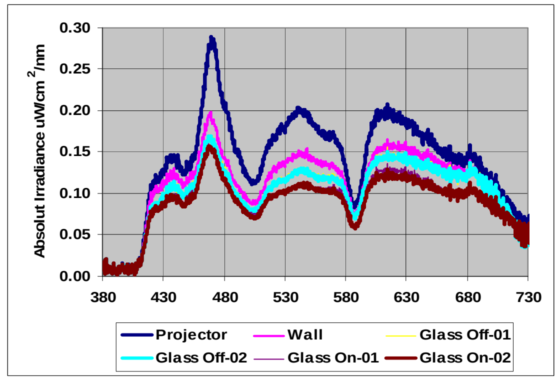
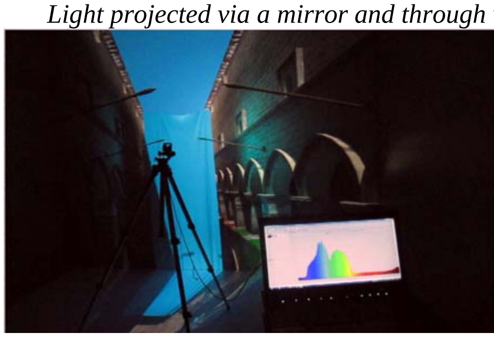


Figure 5, *Measured SPD within the CAVE Light projected via a mirror and through walls*

Figure 6, *Measure SPD with and without 3D-stereoscopic-glass off and on setting*



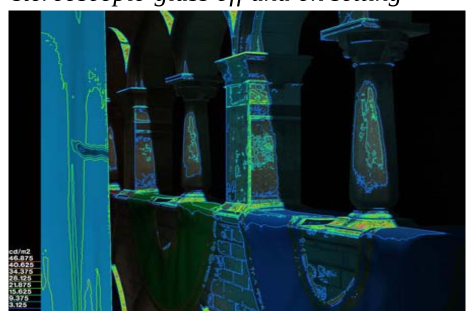


Figure 7, Measured SPD in real time within the animated scene in the CAVE

Figure 8, Measured Luminance distribution of blue reflected light.

The projectors and the CAVE wall surfaces' measured SPD are shown in **Figure 5** including the contribution from infra-red light from motion tracking system. The data was formatted and normalized to the peak wavelength within the range of 380 to 780 nm and used as input to the CQS program for color quality analysis. SPD of a white color scene viewed with and without the 3D stereoscopic-glass were also measured to examine the impact of the 3D glasses on the viewers' color perceptions. The measured results as shown in **Figure 6** show the impact of the 3D stereoscopic-glass on and off settings used to view the scene. There are obvious transmittance losses due to the 3D glass settings. The increase power in the range of 430 to 480 portion of the spectrum as shown in **Figures 7** is due to blue reflections by the blue curtain within the simulated scene. Saturation, CCT and RMS factors are all also calculated (using measured SPD) to evaluate selected simulated scenes not only for calibration but also for architectural applications. As stated in the documentation written for the CQS program by Ohno and Davis, the CQS value (100-RMS_Delta Ei * x) is scaled so that the continuity of the values of the existing lamps are best maintained. The scale is adjusted so that the average of CIE source F1 through F12 (CIE 15.2) is the same. 0-100 Scale: The CQS values that are negative or up to ~20 are converted by a non-linear equation so that the minimum CQS value is zero (i.e., the CQS scale is from 0 to 100). This does not affect CQS values >30. The CRI, CCT and the CQS calculations are summarized in **Table 1.**

Table 1 *- Summary of the color index calculation using measured SPD*

	CCT:	Duv:	CRI Ra:	R(9-12):	R9:	LER (lm/W):
Measured Daylight	5183	0.0095625	95	90	73	250
Avg Projector Mirror	5482	-0.0011292	92	85	57	197
Avg Wall	5547	0.004568	94	83	66	218
Front Projector	5490	-0.0011602	92	85	57	197
Front Wall	5203	-0.0065893	90	82	49	188
Glass Off-01	4950	-0.009572	89	78	46	184
Glass Off-02	4944	-0.0095659	89	79	46	184
Glass On-01	5153	-0.0100027	88	76	44	180
Glass On-02	5281	-0.0085146	89	77	44	179
Blue Wall	5836	-0.0194491	80	54	3	153
Green Wall	5123	0.0024101	94	88	89	186
Red Wall	4012	-0.0233137	82	59	29	159

	CQS	15 samples	Sat. factor	CCT factor	RMS	0-100 scale
Measured Daylight	95	95	95	95	95	95
Avg Projector Mirror	96	94	96	96	96	96
Avg Wall	94	93	94	94	94	94
Front Projector	96	94	96	96	96	96
Front Wall	96	92	96	96	96	96
Glass Off-01	95	92	95	95	95	95
Glass Off-02	95	92	95	95	95	95
Glass On-01	95	90	95	95	95	95
Glass On-02	95	91	95	95	95	95
Blue Wall	89	82	89	89	89	89
Green Wall	94	93	95	95	94	94
Red Wall	90	84	90	90	90	90

The simultaneous projections of the RGB for a given wall within the CAVE provide the opportunity to measure the impact on the viewers' eye due to simultaneous viewing of the RGB walls. The calculated COS and Saturation factor show the degree of change due to these color viewings. The observed differences in CRI, CQS and CCT in **Table 1** indicate the differences are due to the limitation of the sources (projectors) intensities and the color produced within this particular VR geometric environment [1,2,3]**. Figure 9 shows** sample output of the CQS for the CRI index calculation using measured front projector's SPD. These colors do not represent the exact color due to limits of the reproduction of the medium (desktop monitor) used. The solid RED line shows the projector SPD and the associated CIELAB is also shown in the same **Figure 9**.

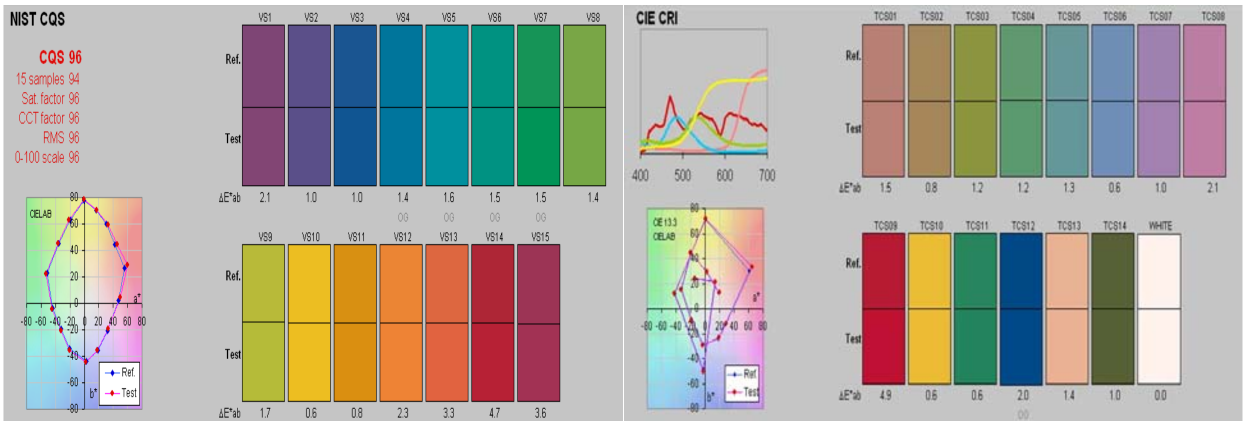


Figure 9, *Sample output for NIST CQS and CRI calculations using measured front projector's SPD*

Conclusion: VR is no longer being viewed as an entertainment system but now is being used in scientific investigation for its visualization capabilities. Some of the lighting design challenges can be solved within the virtual world [**4**]. Although, there are unique applications in which the design objectives demand high accuracy in simulated results, this method may not require absolute accuracy, in order to accelerate the decision making process. The ability to take into account the physical properties of the material do, in fact, impact applications of visualization and prediction of the lighting conditions or perceived colors within each simulated scene. The use of computer generated images within the CAVE could be an alternative to the use of real or full mocked up space during the design concept evaluation. However, many applications like vehicle and street lighting with safety-related issues require a perception-based determination of photometric measures. Virtual reality as a surrogate sensory environment for evaluation of human luminous environment shows a possible path to create a unified system for mesopic luminosity.

References

1. Wyszecki, G., Stiles, W. S. color Science, 2nd ed. (Wiley, 2000).
2. CIE, “Colourimetry and Method of Measuring CRI”, CIE 15 and CIE13.3 -1995, 2004.
3. Davis W. , and Y. Ohno, Toward an Improved color Rendering Metric, Fifth International Conference on Solid State Lighting, edited by Ian T. Ferguson, etl, Proc. SPIE Vol. 5941, 59411G (2005).
4. Navvab, M. Bisegna, F. Gugleirmetti, F., “Evaluation of Historical Museum Interior Lighting System Using Fully Immersive Virtual Luminous Environment”, SPIE Optical Metrology 2013, 13-16, May. 2013, Munich, Germany.

Mojtaba (moji) Navvab, PhD, FIES. Faculty at the U of Michigan, College of architecture since 1985, Chair of the Certificate Program in Simulation Studies at UM-Rackham School of Graduate Studies. A fellow member of the Illuminating Engineering Society of North America (IESNA) 2000. A recipient of five IESNA's International Illumination Design Awards (IIDA). Chair of Technical Committees (TC6- 42) within (CIE). Lighting Aspect of Plant Growth in Controlled Environment. International Advisory Board Member for the Lighting Research and Technology Journal, Research Scientist at the Lawrence Berkeley National Laboratory (1981-1985).