

Spectrally Enhanced Lighting: Related Publications

The following bibliography of publications provides additional information regarding the research that has been performed in this field. Where available, links are included that will either provide a PDF formatted file of the publication or provide a link to a website where the article or publication can be purchased. If you have questions regarding the links listed in the bibliography, contact the Building Technologies Program [webmaster](#).

Year	Author(s), Title, Publication	Important Conclusions
1954	Aguilar and Stiles Saturation of the rod mechanism of the retina at high levels of stimulation Opt. Acta, 59-65.	One of a series of studies (some of those listed below) that finds rods functioning at typical interior light levels but also finds that rods saturate at 2000 scotopic Trolands (the high end of interior luminances around 250 to 300 cd/m ²). Note the typical luminance of a good monitor is around 80 cd/m ² .
1962	Bouma, H. Size of the static pupil as a function of wavelength and luminosity of the light incident on the human eye Nature, 193: 690-691.	Bouma's PhD thesis was the first study to find scotopic dominance of pupil size over a wide range of light levels. The technique used for pupil measurement was entoptic pupilometry, which depends on subject reporting, is considered limited, tedious, and likely biased towards selecting mostly oversized values. That technique has been entirely replaced by infrared technology. Nevertheless the significance of this work never penetrated into the illuminating engineering practice.
1973	Stiles & Wyszecki Rod intrusion in large field color matching Act. Chrom. 2, 155-163.	Another in a series of studies that shows the necessity of rod response at photopic levels in order to explain the data in conditions where the field of view is not a small aperture view.
1976	Rodieck Which two lights that match for cones show the greatest ratio for rods? Vis. Res. 16, 303-307.	This study shows that in a large field of view, cone metamericism alone will not predict equality of brightness perception and that rod function needs to be incorporated for large field brightness matching.
1988	Berman, S.M., Jewett, D.J., Fein, G., Saika, G., and Ashford, F. Photopic luminance does not always predict perceived room brightness Lighting Research Technology, 22(1): 37-41.	First study to show that in full field of view the scotopic content of the observed light needs to be included in order to predict brightness perception. Also provided an approximate quantitative way to include scotopic response by modifying the photopic luminance with the factor $\sqrt{(S/P)}$. The study employed a technique for eliminating confounding chromatic channel effects by combining light sources in a manner to achieve equal chromaticity for the tested illuminants when performing brightness comparisons.

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1990	Hess Rod mediated vision "Night Vision" Cambridge Univ. press.	Discusses the need for including rod response in some aspects of vision at photopic light levels.
1990	Brill Mesopic color matching: some theoretical issues J.OSA A 7, 2048-2051.	Follows the Trezona work from above.
1992	Sharpe, L.T. et al. The field adaptation of the human rod visual system J. Physiol. 445, 319-343	Verifies the conclusions from Hess above.
1992	Berman, S.M., Fein, G., Jewett, D.L., Saika, G. and Ashford, F. Spectral Determinants of Steady-State Pupil Size with Full Field of View JIES, 21(2): 3-13.	Using the techniques of infrared pupillometry and testing many subjects, this study established that at typical interior light levels the pupil is mostly driven by scotopic spectrum but also contains a small photopic component. Generally confirmed the earlier work of Bouma except that his methodology was too coarse to find the photopic component and in addition had the biasing features of entoptic pupillometry. The JIES study also determined the quantitative modifier for photopic luminance as $(S/P)^{0.78}$ that applies to non-computer reading tasks and where there is no supplemental task lighting.
1993	Berman S.M., Fein, G.; Jewett, D.L., and Ashford, F. Luminance controlled pupil size affects Landolt C test performance JIES, 22(2):150-165.	This study demonstrated for young adults that spectrally controlled pupil size at the same photopic luminances was the critical factor for determining best acuity at constant but typical interior light levels.
1994	Shapiro, Pokorny and Smith Rod contribution to large field color matching Color Res. & Appl. 19,4, 236-245.	Added further evidence of rod activity at photopic light levels to the earlier work of Stiles and Wyszecki.
1994	Berman, S.M., Fein, G., Jewett, D.L. and Ashford, F. Landolt C recognition in elderly subjects is affected by scotopic intensity of surround illuminants JIES 23(2): 123-130.	A supplement to the 1993 study of Berman et al., where the tested subjects were 60 years old. The results obtained here confirmed those of the earlier study of young adults.

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1995	Berman, S.M., Fein, G.; Jewett, D.L.; Benson, B.R.; Law, T.M. and Myers, A.W. <u>Luminance controlled pupil size affects word reading accuracy</u> JIES, 25(1): 51-59.	Another study of a group of young adults using a different approach demonstrating that pupil size was a critical factor in determining word reading acuity. Task lighting was held fixed and luminance of the far surround field (greater than 30 deg) was varied. Acuity was better when the luminance of the surround field was higher, which also caused a smaller pupil. Task retinal illuminance was lower in this case but acuity was nevertheless better, confirming that a smaller pupil provided better optical quality with less retinal light.
1996	Shapiro, Pokorny and Smith <u>Cone-rod receptor spaces with illustrations that use CRT phosphor and LED spectra</u> J.O.S.A 13, 12, 2319-2328.	Advanced quantitative procedures for including rod effects in color matching science used in computer technology.
1996	Berman, S.M., Jewett, D.L, Benson, B.R., and Law, T.M. <u>Despite different wall colors, vertical scotopic illuminance predicts pupil size</u> JIES 26(2): 59-68.	The most definitive study in the literature demonstrating that pupil size is controlled by scotopic spectrum. 17 young adults looking at a small TV had their pupils measured by remote infrared pupilometry while seated comfortably in a simulated office under conditions of binocular view and under a variety of light levels and spectra. The mean pupil size variations tracked almost perfectly with the scotopic illuminance at the subject's eye. The practical implication of this study was to show that in a computer environment where the task is self-illuminated, the correct metric for the surround lighting should be scotopic illuminance at the eye and not photopic illuminance at the eye or on a horizontal plane.
1998	Berman, S.M., Jewett, D.L. <u>Two-dimensional photometry for interior surround lighting</u> JIES 27(1): 57-66.	Showed a graphical procedure for determining best vision when comparing lighting of different spectral content for paper reading, computer reading, and room brightness perception.
1998	Fotios, S.A. and Levermore, G.J. Models of the chromatic effect upon brightness perception in interior spaces Lighting Research & Technology, 30(3), 103-106.	Attempted to apply the visual chromatic effect to explain the results of perceived brightness in interior spaces for a number of previous studies. The chromatic effect was not a good predictor.
2000	Berman, S.M. <u>The coming revolution in lighting practice</u> Energy Users News, Oct 25, 10, 23-25.	A general readership article that summarized the results of many of the more technical papers discussed above. The content was primarily to demonstrate how to use the results in lighting design when vision and brightness were key considerations.

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2001	Fotios, S. <u>Lamp colour properties and apparent brightness: A review</u> Lighting Research and Technology, 33(3), 163-181.	An attempt to find quantitative correlates to the results of many studies on the perception of brightness in interior spaces. The various measures considered were all poor predictors. However, in the written discussion of the paper it was shown that applying the square root law ($\sqrt{S/P}$) to those studies where it could be determined provided an excellent predictor for nearly all those studies.
2001	Navvab, M. A comparison of visual performance under high and low color temperature fluorescent lamps JIES, Vol. 30, No. 2, pp.170-175.	This study examined the acuity of some 100 young adults under conditions of equal illuminance but where the spectrum of the lighting was either high or low color temperature. Acuity was significantly better under the high color temperature lighting, confirming previous results of Berman et al., as the higher color temperature lighting also was of higher scotopic content.
2002	Navvab, M. Visual acuity depends on the color temperature of the surround lighting JIES Vol. 31, No. 1, pp. 70-84.	This followed the 2001 study except the conditions were changed. Here task lighting and surround lighting were separately controlled with various devices. Task lighting of fixed spectrum was varied from low to high levels while the surround lighting had either low or high color temperature of fixed and equal photopic illuminance. Word reading acuity was determined as the task light level was varied for the 2 different surround conditions. Two parallel curves of acuity vs. task lighting level were obtained with the better acuity always associated with the higher color temperature lighting. Over a wide range of levels more than 3 times as much task lighting was required for the low color temperature surround condition to achieve the same acuity as for the high color temperature surround.
2004	Liebel, Lee <u>Energy Conservation Using Scotopically Enhanced Fluorescent Lighting in an Office Environment</u> U.S. Department of Energy	This field study was performed to assess the occupant acceptance of the 850 fluorescent lamp (5000K, 85 CRI) in a common office application. Two floors, 30,000 square feet each, had their lighting retrofit with dimming ballasts and new lamps. The baseline floor used 835 lamps that were set to maintain the pre-retrofit illuminance, and the other floor used the 850 lamps with a calculated 20% reduction in illuminance. The study demonstrated 20-30% energy savings and equal occupant acceptance with 850 lamps at reduced lighting levels as compared to the more commonly used 835 lamp in an office.

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2006	<p>Gordon, Sullivan, Armstrong, Richman, Matzke</p> <p><u>Spectrally Enhanced Lighting Program Implementation for Energy Savings: Field Study</u></p> <p>U.S. Department of Energy</p> <p>Liebel, Lee</p> <p><u>Spectrally Enhanced Lighting Program Implementation for Energy Savings: Economics Validation</u></p> <p>U.S. Department of Energy</p>	<p>This field study implemented spectrally enhanced lighting retrofits using 850 lamps and on/off electronic ballasts in three separate buildings in California. The three buildings each had similar lighting systems consisting of 3-lamp, 18-cell parabolic luminaries; however each building had a different lamp and ballast installed: one with 735 T12 and magnetic ballasts; one with 730 lamps and electronic ballasts; and one with 741 lamps and electronic ballasts. The study confirmed occupant satisfaction with the 850 lamps and determined that the visual effectiveness calculations using spectrally enhanced lighting can be effectively used to deliver 19-27% energy savings. The study also monitored task lighting usage and determined there was no additional task lighting usage resulting from the retrofits. The payback for the T12 system was 1.4 years, while the paybacks for the T8 systems were between 3 and 4 years.</p>
2006	<p>Berman, S.M., Navvab, M., Martin, M.J., Sheedy, J.,m Tithof, W.</p> <p><u>A comparison of traditional and high colour temperature lighting on the near acuity of elementary school children</u></p> <p>LR&T Vol. 38, No. 1, 41-49</p>	<p>This study compared the near vision acuity of 27 school children, ages 10-11 years old under the conditions of 3600K and 5500K CCT fluorescent sources. Under the conditions of the 5500K lighting, the visual acuity for 24 of the 27 children was significantly better as compared to using the 3600K lighting at the same luminance. When the 5500K lighting level was reduced to 50% of the luminance of the 3600K lighting condition, there was no significant difference in the visual acuities for the subjects. The study provides further evidence for visual acuity gains from the use of Spectrally Enhanced Lighting.</p>

October 31, 2008