# 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 |
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| 1954 | Aguilar, M., and Stiles, W.S.<br>**Saturation of the rod mechanism of the retina at high levels of stimulation**<br>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.<br>**Size of the static pupil as a function of wavelength and luminosity of the light incident on the human eye**<br>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 toward 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, W.S., and Wyszecki, G.<br>**Rod intrusion in large field color matching**<br>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, R.W.<br>**Which two lights that match for cones show the greatest ratio for rods?**<br>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.<br>**Photopic luminance does not always predict perceived room brightness**<br>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 √(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. |
| 1990 | Hess, R.F.<br>**Rod mediated vision**<br>"Night Vision," Cambridge University Press. | Discusses the need for including rod response in some aspects of vision at photopic light levels. |
| 1990 | Brill, M.H.<br>**Mesopic color matching: some theoretical issues**<br>JOSA A 7, 2048-2051. | Follows the Trezona work from above. |
| 1992 | Sharpe, L.T., et al.<br>**The field adaptation of the human rod visual system**<br>J. Physiol. 445, 319-343. | Verifies the conclusions from Hess above. |

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| 1992 | Berman, S.M., Fein, G., Jewett, D.L., Saika, G., and Ashford, F.<br>**Spectral Determinants of Steady-State Pupil Size with Full Field of View**<br>JIES, 21(2): 3-13. | Using the techniques of infrared pupilometry 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 pupilometry. 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.<br>**Luminance controlled pupil size affects Landolt C test performance**<br>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, A.G., Pokorny, J., and Smith, V.C.<br>**Rod contribution to large field color matching**<br>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.<br>**Landolt C recognition in elderly subjects is affected by scotopic intensity of surround illuminants**<br>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. |
| 1995 | Berman, S.M., Fein, G., Jewett, D.L., Benson, B.R., Law, T.M., and Myers, A.W.<br>**Luminance controlled pupil size affects word reading accuracy**<br>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, A.G., Pokorny, J., and Smith, V.C.<br>**Cone-rod receptor spaces with illustrations that use CRT phosphor and LED spectra**<br>JOSA 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.<br>**Despite different wall colors, vertical scotopic illuminance predicts pupil size**<br>JIES 26(2): 59-68. | The most definitive study in the literature demonstrating that pupil size is controlled by scotopic spectrum. Seventeen 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., and Jewett, D.L.<br>**Two-dimensional photometry for interior surround lighting**<br>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. |

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| 1998 | Fotios, S.A., and Levermore, G.J.<br>**Models of the chromatic effect upon brightness perception in interior spaces**<br>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.<br>**The coming revolution in lighting practice**<br>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. |
| 2001 | Fotios, S.A.<br>**Lamp colour properties and apparent brightness: A review**<br>Lighting Research & 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.<br>**A comparison of visual performance under high and low color temperature fluorescent lamps**<br>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.<br>**Visual acuity depends on the color temperature of the surround lighting**<br>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 two 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 three 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, L.<br>**Energy Conservation Using Scotopically Enhanced Fluorescent Lighting in an Office Environment**<br>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 retrofitted 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. |
| 2006 | Gordon, K.L., Sullivan, G.P., Armstrong, P.R., Richman, E.E., and Matzke, B.D.<br>**Spectrally Enhanced Lighting Program Implementation for Energy Savings: Field Study**<br>U.S. Department of Energy<br><br>Liebel, L.<br>**Spectrally Enhanced Lighting Program Implementation for Energy Savings: Economics Validation**<br>U.S. Department of Energy | 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 luminaires; 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 three and four years. |

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| 2006 | Berman, S.M., Navvab, M., Martin, M.J., Sheedy, J., and Tithof, W.<br>**A comparison of traditional and high colour temperature lighting on the near acuity of elementary school children**<br>LR&T Vol. 38, No. 1, 41-49. | This study compared the near vision acuity of 27 school children, ages 10-11, 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. |
| 2010 | Liebel, B., and Lee, R.<br>Spectrally Enhanced Lighting:<br>Pacific Gas & Electric Company Case Studies<br>U.S. Department of Energy | In this set of case studies, Pacific Gas & Electric Company tested spectrally enhanced lighting technology in seven California commercial office buildings, totaling approximately 300,000 square feet. Three techniques were used to demonstrate the technology: changing lamps and ballasts to 850 lamps with electronically dimming ballasts; switching from recessed lighting fixtures to direct/indirect pendant fixtures, along with changing lamps and ballasts as previously indicated; and retrofitting with highly efficient T5HO lamps in direct/indirect pendant fixtures in open spaces with high ceilings. Each of the techniques created significant energy savings of as much as 65% and building occupants were pleased with the results. |
| 2010 | Liebel, B., and Lee, R.<br>Spectrally Enhanced Lighting:<br>Washington Navy Yard Case Study<br>U.S. Department of Energy | This case study resulted from an energy-saving technologies demonstration program that gave the Washington Navy Yard in Washington, D.C., the opportunity to test out spectrally enhanced lighting in one of its buildings. The three-story police and security building was retrofitted with SEL technology using lighting with an 850 lamp color. This reduced lighting energy consumption in the building by 37.5%. Building occupants responded favorably in surveys about the new lighting. |
| 2010 | Liebel, B., and Lee, R.<br>Spectrally Enhanced Lighting:<br>Alameda County Case Study<br>U.S. Department of Energy<br>. | This case study followed lighting retrofits throughout Alameda County, California, government buildings. The retrofits resulted from an energy audit that revealed spectrally enhanced lighting would significantly reduce lighting costs. A total of 52 buildings were retrofitted with SEL technology using lighting with a lamp color of 850. This upgrade cut lighting electricity costs by 9.3% annually. The vast majority of county employees appreciated the new lighting and the county expects to recoup the cost of the upgrade in 3.56 years. |
| 2010 | Liebel, B., and Lee, R.<br>Spectrally Enhanced Lighting:<br>Los Angeles Public Library Case Study<br>U.S. Department of Energy | This case study reports the results of a building-wide retrofit to spectrally enhanced lighting at the eight-floor, 538,000-square-foot main branch of the Los Angeles Public Library. Lamps with an 850 lamp color, coupled with electronic ballasts, replaced the largely T12 lamps and magnetic ballasts. The retrofit reduced lighting energy consumption by nearly 40% and produces better color rendering for the books and artwork housed in the library. Staff and patrons have expressed appreciation of the new lighting. |
| 2010 | Liebel, B., and Lee, R.<br>Spectrally Enhanced Lighting:<br>Port Hueneme Case Study<br>U.S. Department of Energy | This case study looked at a spectrally enhanced lighting retrofit at a U.S. Navy office building at Port Hueneme in California. Approximately 2,300 overhead lamps were replaced with lamps with an 850 lamp color. Additionally, the electronic instant-start ballasts were replaced with electronic program start ballasts. The retrofit resulted in a 20.5% savings in lighting energy consumption and paid for itself in less than four years. Occupant surveys revealed no significant change in their satisfaction with the lighting. |

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| 2010 | Liebel, B., and Lee, R.<br>Spectrally Enhanced Lighting:<br>San Jose State University Case Study<br>U.S. Department of Energy | In this case study, the result of San Jose State University in California's retrofit of its Dr. Martin Luther King, Jr. Library with spectrally enhanced lighting is examined. Lighting throughout the library was upgraded to SEL technology with a lamp color of 850. For the extensive upgrade, three types of fixtures were used: T5HO lamps coupled with program start ballasts fitted with occupancy sensors, basket troffers arranged as 2x4's with T8 linear fluorescent lamps and 2x2's with biax lamps, and parabolic troffers arranged as 2x4's and 2x2's both with T8 linear fluorescent lamps. The upgrade reduced lighting electricity consumption by 72%. The university recouped the cost of the new lighting in less than two and a half years. Library staff has been pleased with the results. |
| 2010 | Liebel, B., and Lee, R.<br>Spectrally Enhanced Lighting:<br>Santa Rosa Business Office Case Study<br>U.S. Department of Energy | This case study looks at the retrofit of Pacific Gas & Electric Company's 57,800-square-foot Santa Rosa business office in California with spectrally enhanced lighting. Approximately 1,700 overhead lamps with magnetic rapid start ballasts were replaced by lamps with an 850 lamp color and electronic instant start ballasts. The SEL technology reduced lighting energy consumption in the building by 45.6% and paid for itself in less than two years. Occupants were pleased with the results. |
| 2010 | Liebel, B., and Lee, R.<br>Spectrally Enhanced Lighting:<br>U.S. Forest Service Case Study<br>U.S. Department of Energy | This case study followed the U.S. Forest Service's Western Regional Headquarters retrofit of its 119,000-square-foot office building in Vallejo, California, with spectrally enhanced lighting. Approximately 2,800 overhead lamps with electronic instant start ballasts were replaced in the headquarters by lamps with a lamp color of 850 and electronic programmed start ballasts. The SEL technology reduced lighting energy consumption by 19.8% and paid for itself in 3.6 years. Occupants were satisfied with the results. |
| 2010 | Liebel, B., and Lee, R.<br>Spectrally Enhanced Lighting:<br>Sonoma State University Case Study<br>U.S. Department of Energy | This case study analyzes Sonoma State University's retrofit of about 75% of its buildings, or 864,900 square feet, with spectrally enhanced lighting. Where possible and convenient, the lighting was upgraded to lamps with an 850 lamp color. The upgrade reduced lighting energy use by 42% at the university in California. The new lighting is expected to pay for itself in three years. University officials are pleased with the retrofit and plan to upgrade more lighting. |
| 2010 | Liebel, B., and Lee, R.<br>Spectrally Enhanced Lighting:<br>San Ramon Valley Conference Center Case Study<br>U.S. Department of Energy | This case study follows a multi-phase retrofit of lighting at the San Ramon Valley Conference Center in California. The original lighting at the conference center, owned by Pacific Gas & Electric Co., was unreliable and inefficient, so the company decided to retrofit with spectrally enhanced lighting. The lighting was upgraded to lamps with a lamp color of 850 and many fixtures were changed to improve illumination. The upgrades are estimated to have improved lighting energy efficiency by 45%. Anecdotal evidence indicates that staff, students, and other building occupants are pleased with the results. |
| 2010 | Liebel, B., and Lee, R.<br>Spectrally Enhanced Lighting:<br>Fort Wainwright Case Study<br>U.S. Department of Energy | This case study looks at the 91-building retrofit of lighting at the U.S. Army's Fort Wainwright near Fairbanks, Alaska, with spectrally enhanced lighting. There was a great variety of original lighting types. Where possible, lamps were changed to T8s with an 850 lamp color, and magnetic ballasts were changed to electronic ballasts. The SEL technology reduced lighting energy consumption by an estimated 19.6% annually and reduced maintenance costs. The new lighting was well received and the Army has since undertaken several similar projects. |

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| 2010 | Liebel, B., and Lee, R.<br>Spectrally Enhanced Lighting: Veyance Technologies, Inc., Case Study<br>U.S. Department of Energy | This case study analyzed the relatively small-scale retrofit of lighting in 4,000 square feet of office space at Veyance Technologies, Inc., a manufacturing plant in Sun Prairie, Wisconsin, with spectrally enhanced lighting. The original T8s were replaced by T8s with a lamp color of 880. Fewer lamps were needed to achieve the original visual acuity, so each fixture was de-lamped from three lamps to two. The new lamps consume 79% less energy than the original lamps and paid for themselves in 15 months. Employees were pleased with the retrofit. |

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