Raising the Temperature on Lighting:
Acceptance and Energy Savings Potential Utilizing Spectrally Enhanced Lighting

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Abstract

Over the last 20 years, research on Spectrally Enhanced Lighting (SEL) has demonstrated that under light sources with relatively higher Correlated Color Temperatures (CCT) and with the same illuminance levels, pupil size is reduced, brightness perception is increased, and visual acuity is improved. As an energy saving strategy, lighting installations with higher CCT lamps can therefore be designed at lower illuminance levels using less energy because of the compensatory effects that the higher CCT lamps provide, without risk of reduced visual performance. SEL therefore has the potential to provide substantial energy savings and peak demand reduction in commercial buildings through the use of fewer lamps, lower ballast-factor ballasts, and/or fewer luminaires. While the products used in SEL installations are immediately available and cost no more than standard lighting equipment, industry acceptance has not been widespread due primarily to the perception that building occupants would reject relatively higher CCT lighting. This paper provides the scientific background of SEL and details the most recent field studies performed by the US Department of Energy (DOE) that have demonstrated both energy savings and occupant acceptance of SEL. Moreover, this paper demonstrates how the use of this lighting method can realistically permanently reduce the electric lighting load by approximately 25% as compared to standard T8/electronically ballasted lighting and 50% as compared to T12/magnetically ballasted lighting. Finally, the paper concludes that SEL installations have immediate payback for new installations and no more than a 4-year payback for lighting retrofit installations.

Background

Lighting engineering uses metrics that are based on a human visual response to the color of light. Specifically, we evaluate the light output of any given light source by summing the product of the light energy at a specific wavelength multiplied by the relative response of the cone photoreceptors of the eye (as represented by the photopic luminous efficiency function) at that same specific wavelength, for each and every wavelength within the visible lighting range. This method of evaluating light output has been in existence for over 75 years. Light source energy efficiency ratings, quantified by lamp efficacy or Lumens per Watt, are therefore dependent on spectral properties of lighting.

It is well known that the above described measurement system does not fully account for responses of the visual system important to lighting practice. The limitations of lighting measurements is inherent in how the lumen is defined by applying the photopic luminous efficiency function, which is determined under the condition where vision is confined to a very small 2-degree field of view. This small visual field represents less than one-tenth of one percent of the full field of view that is our experience for most normal visual conditions. The limitation of the photopic luminous efficiency function is expressed clearly in the Illuminating Engineering Society of North America Handbook, 9th Edition, page 2-1: "*However, despite the industry-wide acceptance of this function, one should recognize that it represents a compromise in assuming a predictable correlation of physical measurements with visual response, and that there are some circumstances where the system works poorly".*

Recent studies using the more realistic condition of evaluating responses to lighting under a full field of view have conclusively demonstrated that many of the deficiencies encumbering our system of illuminating engineering due to the sole use of the photopic luminous efficiency function can, in fact, be remedied. The majority of these studies were performed at Lawrence Berkeley National Laboratory in the 1990's, including 2 studies on pupil size (Berman et al, 1987 and Berman et al 1992), one study on brightness perception (Berman et al 1990) and three studies on visual acuity (Berman et al 1993, Berman et al 1994 and Berman et al 1996). Other visual acuity studies were performed by Navaab (Navaab 2001, 2002) and a collaborative visual acuity study with school children was conducted by Berman and Navaab (Berman et al 2006) corroborating the earlier visual acuity findings. The conclusion reached in these studies, which collectively include hundreds of subjects, is that under full-field-of-view conditions, true visual effectiveness is best represented when the photopic sensitivity is augmented by an additional spectral sensitivity representative of the non-central photoreceptors with a peak response in the blue-green region around 500nm (whereas the photopic sensitivity function has its peak response at 555nm). Through empirical determination, these studies also conclude that the full-field-of-view response to lighting is best expressed through the use of both photopic and scotopic luminous efficiency functions, from which photopic and scotopic lumen ratings can easily be derived. The inclusion of the additional spectral response for most applications can therefore be accounted for through the application of the ratio of Scotopic to Photopic light quantities – the S/P value – which is based on well-established photometric standards.

The findings from the full-field-of-view research noted above explain previously indefinable gaps between lighting metrics and visual perceptions by including factors that balance the spectral response of both central and non-central photoreceptors. The method utilizing this full-field-of-view model is referred to as the Visual Effectiveness Method. The foundations of the Visual Effectiveness Method can be summarized succinctly; under the conditions of a full field of view, the entire photosensitive region of the eye is collecting light and thus the visual response relies on input from both central and non-central photoreceptors. The contribution of the non-central photoreceptors has been correlated with the scotopic luminous efficiency function, which has a higher sensitivity in the blue-green region than photopic lumens; therefore, lighting that has relatively higher amounts of energy in the blue-green wavelengths, such as higher CCT lamps, will provide increased visual responses. The resultant increase in visual effectiveness can be quantified using the difference in spectral distribution characteristics of the light sources under consideration and the type of task being performed.

The Visual Effectiveness Method has not yet received widespread acceptance in the lighting industry. One reason has been due to some published research that has called to question some of the research findings and conclusions. One such study on visual performance claimed no visual improvement on a visual task using SEL (Boyce, et al 2003); however this study did not control for visual acuity and therefore can justify these claims. A later study by two of the same authors of that study (Akashi & Boyce, 2006) determined that spectrally enhanced lamps can be used to enhance brightness perception to offset reductions in illuminance, which is consistent with the Visual Effectiveness Method. Research at the University of Nebraska – Lincoln (UNL), on the other hand, has claimed that higher CCT lamps may not appear brighter as described by the Berman and Akashi studies (Houser, Tiller & Hu, 2004; Hu, Houser & Tiller, 2006). These UNL studies, however, were not performed in a full field of view and test object brightness rather that the more relevant metric of spatial brightness, making their claims unsubstantiated. Therefore, claims made in these studies that their findings contradict the earlier research are not accurate since the inconsistencies in protocol and test design methods can not be compared. There are no known lighting and vision studies performed with a binocular full field of view that negate the scientific findings used in constructing the Visual Effectiveness Method.

From the design point of view, the primary concern is whether building occupants will accept SEL due to the change in color from what is generally used, i.e. would people accept light that has more blue content in it? Conventional commercial interior lighting practice in the United States generally utilizes lamps with CCT's ranging from 3000K to 4100K. A recent DOE field study comparing the 5000K, 85 CRI (850) lamps to the more commonly used 3500K, 85 CRI (835) lamp found that there was no difference in occupant acceptance between these two light sources, even when illumination levels in the space using the 850 lamps were 20% lower than the space with the 835 lamps (AfterImage + Space, 2004). However, the 2004 study was limited in that it did not retrofit an entire building and the study used dimming ballasts, which are not cost effective for many lighting installations.

Given the preceding background, this field study uses the Visual Effectiveness Method formulas to specify Spectrally Enhanced lamps and fixed output electronic ballasts for full-building retrofits in three buildings to measure and evaluate energy savings, occupant satisfaction, and the cost effectiveness of installing SEL as a retrofit solution in the realistic setting of occupied office buildings. The question asked in this field study is if the Visual Effectiveness Method can be used to save energy in a cost effective way, without risking occupant visual performance or satisfaction with the lighting system.

Study Approach

Three stand-alone office buildings in California were chosen for this study. Each of the three office buildings have over 100 full-time employees working in both private and open offices, the majority of which are in interior (non-daylit) zones. The predominant luminaire type in all buildings is a 3-lamp recessed parabolic luminaire. The field study did not de-lamp luminaires, therefore the variables are limited to the lamp/ballast combinations within the buildings. Buildings were entirely retrofitted with Spectrally Enhanced Lighting, including offices, conference rooms, bathrooms and circulation spaces. Each building had its own installation contractor who was hired directly by the building owner.

The Spectrally Enhanced retrofit lamps were readily available 5000K, 85 CRI (850) T8 lamps for all three buildings. The Visual Effectiveness Method was used to determine the lamp/ballast combinations to be applied in the retrofits. This approach utilizes the photopic lumen ratings and S/P values[1] of the lamps, and the Ballast Factors (BF)[2] of the ballasts. Since there is no change in luminaire distribution, location, or quantity, the change in illuminance varies only as a function of the total lumen output of the lamp/ballast system within the luminaires. Based on the typical reading activities occurring in these office buildings, the designs for the lighting retrofits utilized the Visual Effectiveness factor for paper reading tasks, which has the following relationship between pre- and post-retrofit photopic illuminance $E_{(pre)}$ and $E_{(post)}$ and pre- and post-retrofit S/P values $(S/P)_{(pre)}$ and $(S/P)_{(post)}$:

Equation 1: $$E_{(pre)} \times \left(S/P\right)_{(pre)}^{.78} = E_{(post)} \times \left(S/P\right)_{(post)}^{.78}$$

The simplified expression for the targeted percentage light level reduction is therefore:

Equation 2: % Light Level Reduction $$= \left\{1 - \left(\frac{\left(S/P\right)_{(pre)}}{\left(S/P\right)_{(post)}}\right)^{.78}\right\} \times 100$$

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[1] The S/P value is the ratio of scotopic (S) to photopic (P) output of a light source, as determined by the scotopic and photopic sensitivity functions, respectively. Lamps that have a higher CCT will have higher S/P values.

[2] Ballast factor is the fractional factor applied to lamp rated lumens when used in combination with the specific ballast being used, as compared to the rated lumen output of the same lamp being driven by a reference ballast whose ballast factor is 1.00.

The illuminance values will be proportional to the product of the catalog rated lamp lumens and the ballast factor (BF). In lighting retrofits where only the lamps and ballasts will be replaced without change in fixture configuration or geometry this proportionality factor will be the same for the pre- and post-retrofit conditions[3]. The following therefore is the general formula that follows from equation 1 and was applied to determine the lamp lumen/ballast factor combinations:

Equation 3: $$P_{(pre)} \times BF_{(pre)} \times \left(S/P\right)_{(pre)}^{.78} = P_{(post)} \times BF_{(post)} \times \left(S/P\right)_{(post)}^{.78}$$

Project Protocol

General Approach and Contractor Work Scope

The protocol design was established by the principal investigator and reviewed by an independent third party, including a review by a subcontracted recognized expert in lighting and human factors and an internal review board. The design was structured to mimic, as close as possible, a typical lighting retrofit installation; contractors were free to use their standard methods and means of installation, and building owners used their established methods for communicating with their staff. The lighting retrofits followed typical retrofit installation procedures, whereby all work was performed at night and cleaned up by the following morning.

The selection of lamps and ballasts used in the retrofits was done by first assessing the theoretical post-retrofit photopic lumen output desired using the Visual Effectiveness Method calculations, and then conferring with lamp and ballast manufacturers to decide on the actual equipment that would approximate the desired results. The study strived to use different lamp/ballast combinations for each building as validation of the method and approach that is not dependent on specific products.

The building owners engaged the services of lighting retrofit contractors to install the specified systems in accordance to a Scope of Work provided by the Principal Investigator. Lighting modifications to the overhead lighting systems in offices consisted of retrofitting luminaires with new 850 lamps and electronic ballasts without affecting the optical systems of the fixtures; no luminaires were replaced, removed, relocated, or optically altered. All spaces throughout the building were retrofit, including task lighting, to ensure color consistency throughout the buildings. In the rare case where unusual or incidental lamps (i.e. not 4' T8 lamps) were encountered and no equivalent 850 lamps were available, 841 lamps were used (the cases where this occurred were in non-office spaces within the building) . No modifications were made to the lighting control system.

Building occupants were informed that the lighting retrofits would take place, but were not informed that the color of the lamps would be changed as part of the retrofit. No information about the use of Spectrally Enhanced Lighting was provided to the occupants, although building management was fully informed. Persons with knowledge of the specific nature of the retrofits were not included in the occupant surveys.

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[3] Equation 3 assumes that since there are no changes in the lighting distribution of the fixture, i.e. the luminaire distribution and coefficient of utilization (CU) of the pre- and post-retrofit conditions will be identical. While it is acknowledged that there may be slight changes in luminaire distribution and coefficient of utilization utilization factor associated with the T12 to T8 lamp conversion, these are not considered to be significant for the purposes of evaluating the retrofits proposed here.

Schedule

All three buildings started and completed the process of following the protocol in late summer/early fall of 2005. Building A was the first to start the process, followed by the concurrent installations in Buildings B and C. Monitoring equipment was installed three weeks prior to the beginning of the protocol to ensure proper operation of the equipment. The overhead lighting system power and task lighting usage were monitored throughout the study. The first step taken was to install all new lamps in the fixtures that had the same color temperature as existing so that the comparison between baseline conditions and the retrofit lamps was made using lamps of the same age. The periods between the baseline lamp installation and the baseline occupant survey and the Spectrally Enhanced Lighting retrofit and the retrofit occupant survey were identical; occupants were allowed a 3-week adaptation period prior to being given an online occupant survey to assess their satisfaction with the lighting system, after which they had 2 weeks to respond. Pre- and post-retrofit lighting measurements were taken while the survey was being administered in both baseline and retrofit lighting installations.

Description of Project Sites & Lighting Systems

The following table describes the buildings and their pre-retrofit lighting systems:

Table 1: Overview of Buildings and Pre-retrofit Lighting Systems

	Building A	Building B	Building C
BUILDING DESCRIPTION			
Location	Santa Rosa, CA	Vallejo, CA	Oxnard, CA
Area (sq. ft.)	57,000	119,000	67,000
No. of full-time employees	179	279	209
Open office area cubicles	140	260	176
Private offices	39	19	33
Average ceiling height	11'-0"	9'-6"	9'-0"
PRE-RETROFIT LIGHTING SYSTEM			
Predominant Luminaire	Recessed 18 cell 3-lamp parabolic	Recessed 18 cell 3-lamp parabolic	Recessed 18 cell 3-lamp parabolic
Existing Lamp Type	F34 T12	F32 T8	F32 T8
Existing Lamp Color	735	730	741
Existing Ballast Type	Magnetic Energy Savings, circa 1986	Electronic Instant Start, circa 1999	Electronic Instant Start, circa 1997

As can be seen in Table 1, Building A had T12 lamps and magnetic ballasts, while Buildings B and C had T8 lamps with electronic ballasts, allowing this study to analyze the energy savings of both T12 and T8 retrofits. The baseline fluorescent lamps in each of the buildings had different CCT's allowing this study to analyze the use of the Visual Effectiveness formulas with different S/P values. Of particular interest is Building B, where the change from the pre-retrofit condition of 730 lamps to 850 lamps would conjecturally be a more difficult transition for the employees due to the more significant shift in color appearance.

Lighting System Retrofit Designs

Table 2 provides the manufacturer data and calculated values used for predicting the change in photopic illuminance using the Visual Effectiveness calculations:

Table 2: Pre-retrofit Lighting Systems and Calculated Changes in Illumination Levels Based on Visual Effectiveness Calculations

	Building A	**Building B**	**Building C**
PRE-RETROFIT LAMPS AND BALLASTS			
Lamp	F34T12/SPEC35/RS/EW	F32T8/SP30/ECO	FO32/741/ECO
Lamp Color	735	730	741
Rated Photopic Lumens (P)	2800	2800	2800
Ballast Factor (BF)	0.88	0.88	0.88
Lumen Output (P x BF)	2464	2464	2464
S/P Ratio	1.32	1.30	1.56
Visually Effective Lumens (P x BF) x (S/P).78	3060	3024	3486
POST-RETROFIT LAMPS AND BALLASTS			
Lamp	F32T8/ADV850/XEW	F32T8/XL/SPX50/HLEC	FO30/850XP/SS/ECO
Lamp Color	850	850	850
Rated Photopic Lumens (P)	2400	3000	2800
Ballast Factor (BF)	0.77	0.60	0.71
Lumen Output (P x BF)	1848	1800	1988
S/P Ratio	1.87	2.00	1.85
Visually Effective Lumens (P x BF) x (S/P)$^{.78}$	3011	3091	3212
PREDICTED CHANGES IN LIGHT LEVELS			
Target Light Level Reduction **(Equation B-2)**	24%	29%	12%
Predicted Increase in S/P Ratio	***0.55***	***0.70***	***0.29***
Predicted Change In Photopic Lumens	***-25.0%***	***-26.9%***	***-19.3%***
Predicted Change in Visual Effectiveness	***-1.6%***	***2.2%***	***-7.8%***

The systems used in the lighting retrofits to achieve the equal visual effectiveness described in Table 2 are different for each of the three buildings:

- Building A: 25 Watt, low-wattage T8 lamps and normal low ballast factor ballasts (BF=.77). This approach emphasizes the use of reduced lamp lumens as a means of achieving equal visual effectiveness.
- Building B: "Super" 32 watt T8 lamp and very low ballast factor ballasts (BF=.60). This system uses the extra-efficient, high-lumen version of the more commonly used 32 Watt T8 lamp and reduces energy and light output by using a recently developed ultra-low ballast factor ballast.
- Building C: 30 Watt, slightly lower than regular wattage T8 lamps and slightly lower than regular low ballast factor ballasts (BF=.71). The approach used here is between that of Building A and Building B, avoiding extra-low wattage lamps or extra-low ballast factor ballasts.

The calculations in Table 2 show that the predicted visual effectiveness is within 8% of the pre-retrofit conditions in all cases. This spread is consistent with the confidence levels in the empirical determination of visual effectiveness. The exponent in the visual effectiveness formula has a standard error of 0.03 and the differences are all within 2 standard errors of the exponent.

Table 3 below shows the data and calculated values used for predicting the energy savings and Lighting Power Densities of the proposed lighting retrofits. The data in the Table were provided by the manufacturers for each specific post-retrofit lamp/ballast combination; pre-retrofit system values were taken from manufacturer catalogs and nameplates from pre-existing ballasts.

Table 3: Lighting Retrofit Predicted Energy Savings

	Building A	**Building B**	**Building C**
Average Fixture density (sq. ft. per luminaire)	78	89	71
PRE-RETROFIT LIGHTING ENERGY CALCULATIONS			
Lamp	F34T12/SPEC35/RS/EW	F32T8/SP30/ECO	FO32/741/ECO
Nominal Lamp Wattage	34	32	32
Ballast	Magnetic R.S.	Electronic I.S.	Electronic I.S.
Ballast Configuration	(1) 2-lamp and (1) 1-lamp ballast per luminaire	(1) 4-lamp and (1) 2-lamp ballast per pair of luminaires	(1) 4-lamp and (1) 2-lamp ballast per pair of luminaires
Ballast Wattages	2-lamp = 72 1-lamp = 43	4-lamp = 114 2-lamp = 59	4-lamp = 112 2-lamp = 58
Wattage per Luminaire	115	86.5	85
Lighting Power Density (Watts/sq. ft.)	1.47	0.97	1.20
POST-RETROFIT LIGHTING ENERGY CALCULATIONS			
Lamp	F32T8/ADV850/XEW	F32T8/XL/SPX50/HLEC	FO30/850XP/SS/ECO
Nominal Lamp Wattage	25	32	30
Ballast Manufacturer	Advance Optanium	GE Lighting Ultrastart	Sylvania PSX
Ballast Technology	Electronic Instant Start	Electronic Programmed Start	Electronic Programmed Start
Ballast Configuration	(1) 3-lamp ballast per luminaire	(3) 2-lamp ballasts per pair of luminaires	(3) 2-lamp ballasts per pair of luminaires
Ballast Wattages	3-lamp = 56	2-lamp = 44	2-lamp = 43
Ballast per Luminaire	1	1.5	1.5
Wattage per Luminaire	57	66	64.5
Lighting Power Density (Watts/sq. ft.)	0.73	0.74	0.91
PREDICTED ENERGY SAVINGS			
Predicted Percentage Reduction in Energy	**50%**	**24%**	**24%**

If the lamp/ballast combinations had equal ballast efficiencies, the Visual Effectiveness Calculations for photopic light level reductions would also predict the energy savings, In retrofit scenarios, however, the pre- and post-retrofit ballasts have differing ballast characteristics. In Building A, the change to Spectrally Enhanced Lighting from 735 lamps to 850 lamps and the change in lamp/ballast technology from T12/magnetic ballasts to T8 electronic ballasts contribute equally to the energy savings, i.e. 25% energy savings are from the SEL lamps and 25% from the switch from magnetic to electronic ballasts. For Building B, the extremely low ballast factor programmed start ballasts used in the retrofit are not as efficient as the 1999 pre-retrofit electronic instant start ballasts, however, the reduction in overall power consumption is still predicted to be 24% due to the reduction in lighting allowed under the Visual Effectiveness calculations. For Building C, the retrofit programmed start ballasts are 5% more efficient than the 1997 pre-retrofit electronic instant start ballasts, showing that 80% of the energy savings will come from Spectrally Enhanced Lighting and 20% will come from increases in ballast efficiency.

Results[4]

Lighting Measurements

The illumination measurements include horizontal illumination measurements at desk height and vertical illumination measurements at eye height in sitting position, looking toward the office partitions or walls. The horizontal measurements are considered the most reliable to assess light level reduction in the space, while vertical illumination at the eye is considered when analyzing occupant reactions to lighting. The equipment used for taking light level measurements had both Scotopic and Photopic measurement capability, providing the actual pre- and post-retrofit S/P values within the spaces.

Table 4: Data Summary - Illuminance and S/P Ratios

	Units	Bldg. A	Bldg. B	Bldg. C
LIGHTING MEASUREMENTS				
HORIZONTAL MEASUREMENTS				
Horizontal Photopic Illuminance				
Mean Before Retrofit	Lux	461.75	468.37	558.20
Mean After Retrofit	Lux	370.45	321.29	474.09
Statistical Difference	Lux	-92.00	-147.00	-84.00
Confidence Interval on Difference	+ Lux	14.00	18.00	15.00
Percent Difference	%	-20%	-31%	-15%
Horizontal S/P Ratio				
S/P Before Retrofit	Num	1.29	1.27	1.59
S/P After Retrofit	Num	1.81	1.86	1.90
Difference in S/P Ratio	Num	0.52	0.59	0.31
Confidence Interval on Difference	+ Num	0.03	0.02	0.02
VERTICAL MEASUREMENTS				
Vertical Photopic Illuminance				
Mean Before Retrofit	Lux	168.45	151.84	165.38
Mean After Retrofit	Lux	126.35	104.86	150.75
Statistical Difference	Lux	-42.00	-47.00	-15.00
Confidence Interval on Difference	+ Lux	13.00	10.00	12.00
Percent Difference	%	-25%	-31%	-9%
Vertical S/P Ratio				
S/P Before Retrofit	Num	1.26	1.26	1.54
S/P After Retrofit	Num	1.73	1.81	1.83
Difference in S/P Ratio	Num	0.47	0.55	0.29
Confidence Interval on Difference	+ Num	0.02	0.02	0.04

Due to the predominance of direct lighting distribution from the recessed parabolic luminaires, it is assumed that the predictions of the change in illuminance would translate more directly to the horizontal measurements than the vertical measurements. The predicted and measured percent reductions in horizontal photopic illuminance are within 5% of each other (comparing results in Table 4 to the predicted photopic illuminance reductions in Table 2).

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[4] The third party measurements were made by PNNL. For the sake of brevity, summaries of the findings are reported here, as the full report is over 100 pages long. The full report describing the methods and statistical analysis can be found on the PNNL website (Gordon et al 2006).

S/P Ratio Measurement Analysis. The S/P values determined from the measurements listed in Table 4 are compared in Table 5 to the catalog S/P values, as provided by lamp manufacturers:

Table 5: S/P Ratio Measurement Analysis: Compares catalog S/P values based on manufacturers' data to measured S/P values

S/P Ratio Shift			
Predicted Increase in S/P Ratio	***0.55***	***0.70***	***0.29***
Measured Increase in Horizontally Measured S/P Ratio	0.52	0.59	0.31
Measured Increase in Vertically Measured S/P Ratio	0.47	0.55	0.29

The Measured S/P values are expected to be different from manufacturer's S/P values once lamps are introduced into a space, since the color characteristics of the lighting within a space are affected by surface colors such as walls and partition systems. The measurements of the horizontal S/P Ratio show varying differences when compared to the manufacturer data: The Building A S/P Ratio is .06 less than the manufacturer's data, Building B measurements are .14 less than manufacturer's data, and Building C is .05 higher than manufacturer's data. The difference between the manufacturer's data and the measured levels in Building B seems disproportionate given that the neutral colors of the space would not be expected to create such a difference.

The vertical S/P ratio is lower than the horizontally measured S/P ratio in all cases. The reduction in S/P ratio from the horizontal measure to the vertical measure is .08 in Building A, .05 in Building B, and .07 in Building C. These shifts show a general trend of lower S/P ratios when measured at eye position from the horizontal S/P measurement (difference ranging between .05 and .08). This shift in S/P ratios is consistent with the neutral, but slightly warmer colored partitions in the buildings.

Visual Effectiveness Analysis. The results in Table 4 are used to calculate the actual Visual Effective Illuminance (VEE) values, and compare them to predicted values. There is a small difference in the pre/post predicted VEE values because the combined lumen output of the retrofit lamp ballast system does not perfectly satisfy the conditions of equation 3. Based on the measured illuminance values these differences become somewhat larger. The following Table 6 summarizes these calculations:

Table 6: Visual Effectiveness Analysis. Compares predicted Visual Effective Illuminances (VEE) changes to calculated values based on measured photopic illuminance and S/P ratios

	Bldg. A	**Bldg. B**	**Bldg. C**
Predicted Change in Visual Effectiveness (Table 2)	***-1.6%***	***2.2%***	***-7.8%***
Visual Effectiveness Calculations - Horizontal VEE			
Pre-retrofit Horizontal VEE	563.21	564.36	801.46
Post-Retrofit Horizontal VEE	588.46	521.34	782.15
Change in Horizontal VEE	4.5%	-7.6%	-2.4%
Difference, Measured Values - Predicted Value	6.1%	-9.8%	5.4%
Visual Effectiveness Calculations - Vertical VEE			
Pre-retrofit Vertical VEE	201.73	181.83	231.61
Post-Retrofit Vertical VEE	193.75	166.57	241.53
Change in Vertical VEE	-4.0%	-8.4%	4.3%
Difference, Measured Values - Predicted Value	-2.4%	-10.6%	12.1%

The horizontal illuminance measurements are used to test how close the predicted changes in VEE are to the measured conditions. Buildings A and C show that the measured values indicate a slight increase over the predicted VEE that are consistent with the confidence limits discussed in connection with Table 2. Building B shows a nearly 10 percentage point reduction from what was predicted, which is larger than the 2 standard error limit discussed in Table 2. This resulted from having a lower actual S/P ratio than expected when compared to manufacturer provided data, and may have implications on occupant satisfaction or task lighting use, since brightness perception and the ability read paper tasks could both be negatively affected.

The vertical measurements may provide insight into occupant satisfaction ratings. Building A calculations are very consistent with the predicted Vertical VEE, while the calculations for Building B are 10.6% percentage points lower than the predicted Vertical VEE. The calculations for Building C are12.1 percentage point higher than the predicted Vertical VEE, which is counter to predictions and not readily explainable.

Overhead Lighting Power Measurements

Connected Load Analysis. The connected load analysis uses the measured pre- and post connected loads on a per-luminaire basis to determine the power reductions and hence the eventual energy savings of the lighting retrofit. The direct translation from changes in connected load to energy savings is appropriate in this case, since no additional measures were taken to change the time element of the energy equation, Energy = Power x Time. Furthermore, the direct comparison of connected load on a per-lamp or per-luminaire basis provides a basic check on assumptions and calculations made based on manufacturer-supplied information. The measured reductions in connected load were: Building A, 45.6%; Building B, 19.8%; Building C, 20.5% These reductions ranged between 3.6% and 4.8% lower than predicted in all three buildings. The differences between calculated values and measured values may be due to temperature and/or voltage differences between actual field measurements and equipment tested under laboratory conditions.

Lighting Power Density Analysis. Lighting Power Densities (LPD) are used as a means of assessing the power consumption of lighting within a building. The use of the LPD metric is used throughout the United States in energy conservation standards to limit the amount of power used for lighting buildings, based on the building types and currently available energy-efficient lighting technologies. The following table shows the extension of the measured findings of watts per luminaire to Lighting Power Density (Watts per sq. ft.):

Table 7: Pre- and Post- Retrofit Predicted and Measured Lighting Power Densities

	Bldg. A	Bldg. B	Bldg. C
Average sq. ft. / Luminaire	***78***	***89***	***71***
Pre-Retrofit LPD			
Pre-Retrofit Calculated LPD (Table 2-3)	1.47	0.97	1.20
Calculated LPD based on Measured Conn. Load	1.45	0.98	1.15
Post-Retrofit LPD			
Post-Retrofit Calculated LPD (Table 2-3)	0.73	0.74	0.91
Calculated LPD based on Measured Conn. Load	0.79	0.79	0.91

Table 7 shows that the resultant Lighting Power Densities for Buildings A and B are quite similar at .79 Watts per sq. ft. measured. These end up with the same LPD in spite of different luminaire densities due to the relative efficiencies of the lamp/ballast system; while Building A had a higher luminaire density than Building B, the relative lamp/ballast system efficiency due to the instant start ballast technology was higher and the end result for the LPD was identical. Compared to Building A, Building C has a higher LPD due to the increased luminaire density and the slightly less efficient programmed start ballast technology (as compared to Building A's instant start ballasts). Buildings A and B show a slightly higher than predicted LPD due to the differences in the per-luminaire Wattages.

Task Lighting Usage

Task lighting usage is an important consideration when assessing the overall effectiveness of lighting retrofits. When light levels from overhead lighting systems are reduced, occupants could, if the Equivalent Visual Effectiveness concept was incorrect, make up for the reduced illumination by turning on their localized task lighting more often. Such a result could defeat the energy savings for the building. Task lighting was continuously monitored in all three buildings, and questions on the use of task lighting were also included in the online occupant survey. This provides an objective measurement and a subjective response to the question of task lighting usage, and allows a comparison of the results. Task lighting usage measurements are summarized in the following tables:

There was no statistically significant change in the task lighting usage in any of the three buildings. In Buildings A and C, there was a slight decrease in task lighting usage; in Building B, there was a slight increase in task lighting usage. The increase in task lighting usage in Building B, although not statistically significant, is consistent with expectations resulting from the lower actual values of both horizontal and vertical VEE as compared to the calculated values (- 7.6% and -8.4%, respectively).

The lack of any significant change in task lighting usage indicates that the Visual Effectiveness formulas can be applied without risk of increase in the use of task lighting, even with reduced photopic illuminance values.

Occupant Ratings of Satisfaction with the Lighting System

This study provided the opportunity to evaluate the concern of occupant response to 850 lamps in an office environment. An online survey was issued to all full-time occupants to assess their levels of satisfaction with the lighting before and after the lighting retrofit to clearly establish differences in occupants' ratings of satisfaction with the lighting between the pre- and post-retrofit lighting conditions. The occupant survey used questions taken from the Center for the Built Environment Occupant Indoor Environmental Quality Survey. The survey instrument uses a 7-point scaling system, ranging from negative to positive. The Survey contained three questions related to occupant satisfaction with lighting:

1. How satisfied are you with the light level in your workspace?
2. How satisfied are you with your visual comfort under this lighting?
3. Overall, does the lighting quality enhance or interfere with your ability to get your job done?

These questions were asked, along with other information on age, gender, type of computer monitor, and other non-lighting questions, three weeks after the baseline lamp installation and three weeks after the retrofit installation. The survey therefore asked the same questions to the same people after the same adaptation period from when the two different lamps were installed in each building. The statistical analysis uses paired results; that is, the difference between the pre- and post-retrofit responses for each question were evaluated on a per-person basis and the results of the shifts in responses from pre-to post-retrofit, per person, were analyzed for statistical significance.

Table 8: Summary of Occupant Ratings of Satisfaction with the Lighting

	Units	Bldg. A	Bldg. B	Bldg. C
OCCUPANT SATISFACTION SURVEY RESPONSES				
Question: How satisfied are you with the light level in your workspace? 1=Very Dissatisfied, 7=Very Satisfied				
Mean Before	Rank	5.15	5.24	5.49
Mean After	Rank	5.23	5.26	5.56
Statistically Different?	Yes/No	N	N	N
Question: How satisfied are you with your visual comfort under this lighting? 1=Very Dissatisfied, 7=Very Satisfied				
Mean Before	Rank	4.9	5.04	5.29
Mean After	Rank	5.1	5.06	5.48
Statistically Different?	Yes/No	N	N	N
Question: Overall, does the lighting quality enhance or interfere with your ability to get your job done? 1=Inteferes, 7=Enhances				
Mean Before	Rank	4.62	4.88	5.26
Mean After	Rank	5.03	5.03	5.28
Statistically Different?	Yes/No	Y	N	N
Statistics on Surveys				
No. of full-time staff surveyed	Num	143	256	186
No. of full-time workers responding to pre-retrofit and post-retrofit surveys	Num	63	145	88
Percentage of full-time workers responding to pre-retrofit and post-retrofit surveys	%	44%	57%	46%
Statistical difference between age groups?	Yes/No	N	N	N
Statistical difference between genders?	Yes/No	N	N	Y

Table 8 clearly shows that for the three buildings tested, there were no decreases in occupant ratings of satisfaction when the lighting was changed to Spectrally Enhanced Lighting under the conditions of reduced photopic illuminance; all ratings of satisfaction increased with the use of the Spectrally Enhanced Lighting, although only one of them to a statistically significant level (Question 3, Building A). These results demonstrate that the 850 lamp can confidently be used in commercial office buildings under the conditions of reduced photopic illuminance through the use of the Visual Effectiveness formulas without risk of a loss in occupant satisfaction with the lighting.

Economic Analysis

A Life-Cycle Cost-Benefit analysis was performed on the three buildings. The analysis used a 20 year system life, opportunity rate of 7%, California utility rate of $0.15 per kWh and 3350 annual hours. The analysis used thee same values for all three buildings. The labor and materials costs were provided by each of the installing contractors and were actual costs to the building owner. The payback for these projects were: Building A, 1.4 years; Building B, 3.6 years; and Building C, 3.5 years.

Conclusions

The conclusions drawn from this study are that Spectrally Enhanced Lighting can be used as an energy efficient lighting retrofit technique that yields 19 to 27% energy savings while providing equal satisfaction to pre-retrofit conditions of lower CCT lamps at higher illuminance values. Furthermore, the Visual Effectiveness Method used to engineer the lighting retrofit solutions proved to be an effective means of predicting light levels and energy savings. The amount of energy savings obtained is about the same as from the widely accepted conversion of T12/magnetic ballasts to T8/electronic ballasts.

The basis of light level reductions used in this study is maintaining equal visual effectiveness, using the Visual Effectiveness Method calculations. No efforts were made to arbitrarily reduce the illuminance levels, however, it could be argued that additional energy savings could be gained through reductions in illuminance, if the existing buildings were overlit. If a building owner and lighting practitioner agree that the general lighting levels can be reduced, a new target illuminance could be assumed, and the visual effectiveness formulas applied to the new reduced illuminance targets.

This study is also the first to test the design of the Visual Effectiveness Method using fixed output ballasts. All other studies have used dimming ballasts due to the uncertainties of occupant satisfaction with the reduced illuminance level. The results show that building owners can confidently use fixed output ballasts in SEL retrofits, which is necessary for these installations to be cost effective.

The significance of this field study is in the conclusive evidence it provides as to occupant satisfaction with the 850 Spectrally Enhanced lamps when designed using the Visual Effectiveness Method. This field study provides clear evidence of occupant satisfaction in three independent buildings with this lighting as compared to 730, 735, and 741 lamps, demonstrating that even when the change in color is as much as 2000K, the occupants were just as satisfied with the lighting as they were prior to the retrofit. These installations were performed in as realistic conditions as possible in real working environments; the building owners hired their own contractors and the work was done by the contractors in accordance with standard practice. The major concern of the lighting design community has therefore been addressed in this study.

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