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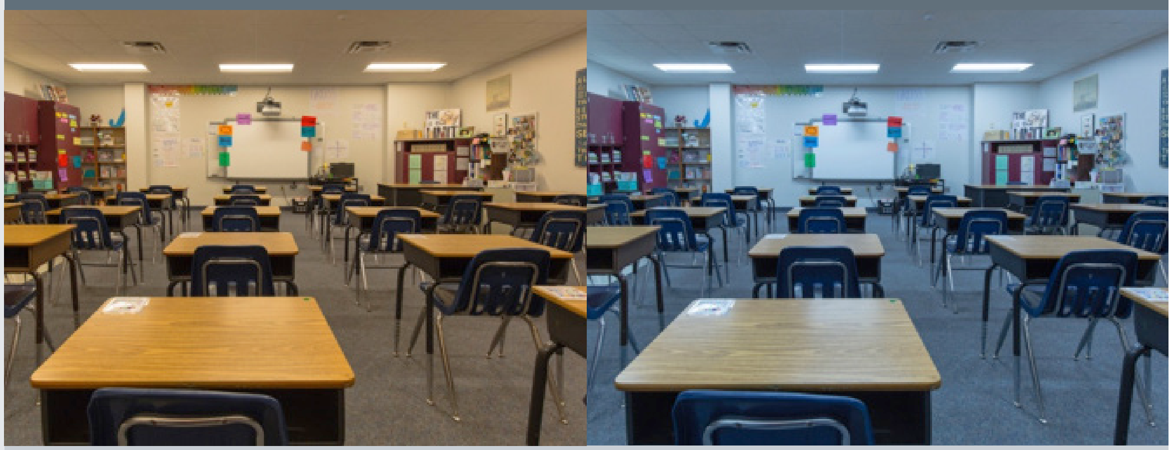
Tuning the Light in Classrooms:

Evaluating Trial LED Lighting Systems in Three Classrooms at the Carrollton-Farmers Branch Independent School District in Carrollton, TX

Prepared for the U.S. Department of Energy
Solid-State Lighting Program

September 2017

Prepared by Pacific Northwest National Laboratory



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Prepared in support of the DOE Solid-State Lighting Technology GATEWAY Program

Study Participants:
Pacific Northwest National Laboratory
U.S. Department of Energy
Carrollton-Farmers Branch Independent School District
Estes, McClure & Associates, Inc.
Acuity Brands Lighting

Robert G. Davis
Andrea Wilkerson

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Preface

The U.S. Department of Energy's Solid-State Lighting program documents the performance of SSL products and systems based on standardized laboratory test results, additional specialized testing, mock-up studies, and real-world field evaluations. This information is provided publicly for several purposes: 1) to track SSL technology performance improvement over time; 2) to identify technology challenges that impact performance and application of SSL; 3) to spur continued advancements in SSL technology, product design, and application; and 4) to maximize energy efficiency and decrease U.S. energy use, while improving lighting quality. DOE does not endorse any commercial product or in any way provide assurance that other users will achieve similar results through use of these products. SSL technology continues to evolve quickly, so evaluation results should always be understood in the context of the timeframe in which products were acquired, tested, installed, and operated. Especially given the rapid development cycle for SSL products, specifiers and purchasers should always seek current information from manufacturers when evaluating such products. The two programs primarily involved in product evaluations are CALiPER and GATEWAY.

CALiPER

When CALiPER was launched its role was largely to test products and compare actual performance to manufacturer claims and to benchmark technologies. Early CALiPER testing also contributed fundamentally to the development of standardized photometric test methods specifically for SSL and the associated accreditation of testing laboratories. As the SSL market has matured, CALiPER has transitioned its evaluations to new products and functions, such as OLED-based luminaires and color tunable products, as well as long-term product performance. CALiPER continues to support the development of new test procedures and application guidance, with DOE investigations providing data that is essential for understanding the most current issues facing the SSL industry. Data are gathered primarily through laboratory testing and mock-up installations.

GATEWAY

GATEWAY conducts field evaluations of high-performance SSL products to collect empirical data and document experience with field installations. GATEWAY provides independent, third-party data for use in decision-making by lighting manufacturers, users, and other professionals. Real-world installations often reveal product limitations and application issues that are not apparent from laboratory testing. GATEWAY typically documents pre- and post-installation light levels, color characteristics, energy intensity, and other performance attributes, and addresses application and maintenance of SSL products. In some cases, GATEWAY returns to projects after months or years of operation to take additional site measurements or remove luminaires and send to accredited laboratories for testing. While not possible for every project, such follow-up measurements have yielded useful data on dirt depreciation, color shift, luminous intensity distribution changes, and lumen depreciation over time.

For more information on the DOE SSL program, please visit http://www.ssl.energy.gov.

Acknowledgements

This project would not have been possible without the full collaboration and cooperation of the following individuals from each of the participating organizations. They were generous with their time and information, and they were always very responsive to our inquiries and requests. Their commitment to their roles within their organizations and to providing the best possible educational environment for students was inspiring. We are very grateful for their contributions.

Carrollton-Farmers Branch Independent School District:

Facilities: Victor Melton

Teachers: Jenna Jones, Carolyn Parker, Barry Rose

Principals: Lance Hamlin, Amy Miller, Lisa Williams

Estes, McClure & Associates, Inc.: Catherine Hollenshead

Acuity Brands Lighting: Tricia Foster, Kyle Gotliebson

Executive Summary

This report summarizes the results from a trial installation of light-emitting diode (LED) lighting systems in three classrooms in the Carrollton-Farmers Branch Independent School District (CFB) in Carrollton, TX. In collaboration with the school district, the lighting system manufacturer (Acuity Brands Lighting, ABL), and the consulting engineers (Estes, McClure & Associates, EMA), the U.S. Department of Energy (DOE) documented the performance of the LED lighting systems as part of a GATEWAY evaluation. Pacific Northwest National Laboratory (PNNL) conducted the investigation on behalf of DOE. EMA and ABL completed the design of the LED lighting systems, and coordinated installation with CFB facilities staff. DOE evaluated the photometric performance of the systems.

The three classrooms included in the LED lighting system installation and evaluation were a fifth-grade math and science classroom, a fourth-grade reading and language arts classroom, and an eighth-grade science laboratory. In each case, there was a very similar classroom located nearby that retained the incumbent fluorescent lighting system, and that was used as a base case reference for comparison to the LED lighting system. All three schools were originally opened prior to 1990. The predominant incumbent classroom lighting system consisted of recessed 2 ft by 4 ft luminaires with four T8 fluorescent lamps (rated at 32 W) and two 2-lamp electronic ballasts in each luminaire. This lamp-ballast combination resulted in 108 W per luminaire.

The LED lighting systems were installed in August 2016, immediately prior to the start of the 2016-2017 school year. Each recessed fluorescent luminaire was replaced with a 2 ft by 4 ft Lithonia Lighting® BLT Series Tunable White LED luminaire from ABL. Luminaire locations remained the same. These luminaires offer tunable white lighting with a correlated color temperature (CCT) range of 3000 to 5000 K. The 4800 lm light output option was specified for the classrooms, and this option results in a rated light output ranging from about 4600 to 5000 lm and input power ranging from 34 to 45W at full output. The luminaires were specified with a curved diffuser with linear prisms and with an nLight® nTune™ control interface.

The lighting control system provided the ability to vary the spectral power distribution (SPD) of the lighting across four pre-set conditions, associated with nominal CCTs of 3000 K, 3500 K, 4200 K, and 5000 K. The controls also provided for pre-set scene controls to vary the on/off status and dimming level of different luminaire zones within the room, to better support classroom functions such as AV presentations and student speeches.

Key results from the trial installation included the following:

- The reduction in input power for the tunable-white LED lighting system used in the three classrooms was estimated to be 58% relative to the incumbent fluorescent system. This reduction in luminaire power is attributable to the higher efficacy of the LED luminaires and a reduction in illuminances, which previously exceeded IES-recommended levels.
- The dimming incorporated into the scene controls and separate up and down dimming controls furthered the energy savings in each classroom. While the individual teacher's usage of the controls varied widely, in each case the lighting consistently operated with all or some of the luminaires turned off or dimmed for portions of the school day.
- The LED lighting systems were installed and commissioned with very few difficulties, and any issues with initial performance were quickly resolved.

- The three teachers involved used the scene controls regularly during the school day, but used the SPD controls infrequently.
- Illuminance levels in the classrooms at maximum output met or exceeded IES recommendations for the typical visual tasks, with both the new LED and the incumbent fluorescent systems.
- Color consistency for the tunable white LED luminaires used in the classrooms was very good among luminaires and very good over the dimming range, with minor variations in CCT and D_{uv}.
- The two teachers interviewed by DOE appreciated the ability to tailor the lighting to different classroom needs, and felt that the lighting and controls allowed the students to be engaged in choosing the settings for various classroom activities. Both teachers stated that the lighting system improved the overall learning environment.

Beyond these key results, this project also provided insight into the use of color-tunable LED lighting to achieve non-energy benefits. The combination of spectral tuning and dimming in the classrooms provides greater opportunity to vary lighting parameters that may affect circadian and behavioral responses for students, teachers, and other users of the classrooms, relative to the fluorescent systems. While documenting these circadian and behavioral effects was beyond the scope of this project, the tunable LED systems may be adaptable to reinforce the desired outcomes, should scientific consensus emerge that supports specific SPD and intensity settings for related effects.

Energy savings from tunable classroom systems results from the switching and dimming functionality of the scene control settings and the manual dimming controls; the ability to vary the color temperature does not necessarily provide additional energy savings. Because color-tunable systems are at present more costly than fixed-color LED systems (which can still provide full scene and dimming control), an economic argument for color-tunable systems cannot be based on energy alone. Like other classroom upgrades (better furnishings, better instructional technology, better air quality, etc.), the justification for color-tunable systems needs to include non-energy benefits related to a better learning and working environment, possibly linked to student learning outcomes, teacher satisfaction and retention, and human health impacts. The difficulty in documenting and assigning economic value to these potential non-energy benefits poses a major challenge for color-tunable lighting systems in classrooms and other applications.

Contents

1. Introduction

This report summarizes the results from a trial installation of light-emitting diode (LED) lighting systems in three classrooms in the Carrollton-Farmers Branch Independent School District (CFB) in Carrollton, TX. In collaboration with the school district, the lighting system manufacturer (Acuity Brands Lighting, ABL), and the consulting engineers (Estes, McClure & Associates, inc., EMA), the U.S. Department of Energy (DOE) documented the performance of the LED lighting systems as part of a GATEWAY evaluation. Pacific Northwest National Laboratory (PNNL) conducted the investigation on behalf of DOE. EMA and ABL completed the design of the LED lighting systems, and coordinated installation with CFB facilities staff. DOE evaluated the photometric performance of the systems.

The three classrooms included in the LED lighting system installation and evaluation were

- a fifth-grade math and science classroom at Dale B. Davis Elementary School (DES),
- a fourth-grade reading and language arts classroom at Sheffield Elementary School (SES), and
- an eighth-grade science laboratory at Charles M. Blalack Middle School (BMS).

In each case, there was a very similar classroom located nearby that retained the incumbent fluorescent lighting system, and that was used as a base case reference for comparison to the LED lighting system. An exterior view of each school is shown in Figure 1. All three schools were originally opened prior to 1990. Details on the lighting systems are provided in Section 2.

Lighting has historically been the second largest energy use for the CFB; only cooling has required more energy. Plug load energy use has increased dramatically through the rapid growth in the use of computers and other types of office equipment and appliances; as a result of this growth, coupled with the growing adoption of energy efficient lighting systems, plug load energy use now exceeds lighting energy use in the district. Nevertheless, reducing the energy used for lighting remains a priority for the district.

However, the district's objectives for the trial installation included considerations beyond energy savings. Based on previous small-scale installations of LED lighting, the district viewed this trial as an opportunity to gain further experience with LED lighting and controls technology. Through the installation of fully tunable LED lighting systems, with control over both the intensity and spectrum of light, the district hoped to assess the potential for tunable lighting to enhance teacher engagement with students and to improve student performance. Several recent studies[1] indicated that tunable lighting may improve student concentration and performance, and CFB wanted to gain some first-hand experience with the technology, to consider more widespread adoption if future evidence confirms the positive effects on student achievement.

[1] For example, see Wessolowski et al., *The effect of variable light on the fidgetiness and social behavior of pupils in school*, Journal of Environmental Psychology 39 (2014); Sleegers et al., *Lighting affects students' concentration positively*, Lighting Research & Technology (2012); Mott et al., *Illuminating the effects of dynamic lighting on student learning*, SAGE Open (2012); and Barkmann et al., *Applicability and efficacy of variable light in schools*, Physiology & Behavior 105 (2012).

Figure 1. Exterior view of the three schools in the Carrolton-Farmers Branch Independent School District that participated in the LED lighting system installation and evaluation project. One classroom in each school was outfitted with a new lighting system. (Credits: ABL for DES, PNNL for others.)

2. Classroom Lighting System Evaluations

2.1 Incumbent Systems

The predominant classroom lighting system in CFB schools at the time of the trial LED lighting installation consisted of recessed 2 ft by 4 ft luminaires with four T8 fluorescent lamps (rated at 32 W) and two 2-lamp electronic ballasts in each luminaire. This lamp-ballast combination resulted in 108 W per luminaire.[2] Figure 2 shows the fluorescent lighting system in the reference classroom at DES.

Figure 2. The reference classroom at Dale B. Davis Elementary School, with the incumbent nine-luminaire fluorescent lighting system.

Because the prevailing energy code at the time required bi-level switching, each classroom has two wall switches located near the door. One switch controls two of the lamps in each luminaire and the other switch controls the other two lamps in each luminaire. This general control scheme was modified to support AV presentations by identifying luminaires within an AV zone (such as those near a whiteboard or smartboard where images are presented), and controlling all the lamps within those luminaires from a single switch. This enabled the teacher in a classroom to completely turn off the luminaires within the AV zone, while keeping half of the lamps on in other parts of the room if desired for student note taking. A schematic of this switching scheme is provided in Figure 3. Each of the three classrooms studied and the respective reference classrooms used this type of bi-level switching scheme, modified for AV presentations.

[2] Based on manufacturer-rated system data for a two-lamp electronic ballast with normal ballast factor of 0.87 driving two 32 W T8 fluorescent lamps.

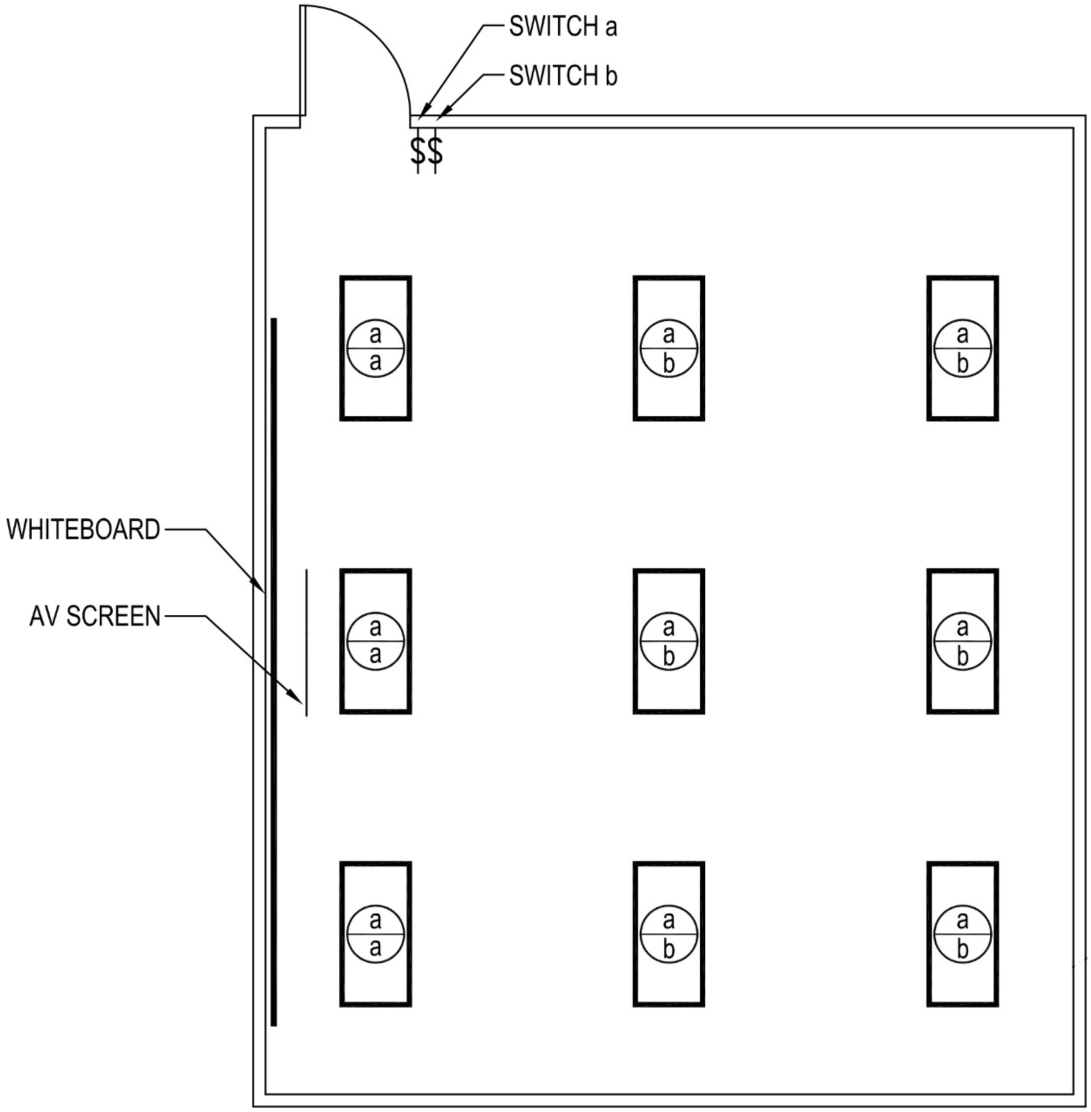

Figure 3. **Switching schematic for the incumbent fluorescent lighting systems. Switch "a" controls two lamps in six of the luminaires and all the lamps in the three luminaires in the AV zone. Switch "b" controls the two lamps not controlled by Switch "a" in the six luminaires that are not in the AV zone. (Image credit: EMA)**

While most classrooms in the district use a nine-luminaire system with T8 fluorescent lamps similar to the system studied at DES (and as illustrated in Figure 2 and Figure 3), the classrooms studied at SES and BMS are larger, with the classroom at SES having 12 luminaires and the classroom at BMS having 17 luminaires. The classrooms studied at SES had not been upgraded to the typical T8 system used throughout the district at the time of the project; these rooms had an older fluorescent system consisting of 34 W T12 cool white fluorescent lamps.[3]

All of the classrooms in the study (incumbent and LED) had motion (occupancy) sensors that switched off all the room lighting if no motion was detected in the room after a defined time period, and that switched the lights back to their prior state when occupancy was again detected. The incumbent motion sensors were replaced in the trial LED rooms with models that would be compatible with the new control systems.

[3] An electronic ballast driving two of these lamps is rated for 62 W, so these luminaires have a total rated power of 124 W.

2.2 LED Systems

The LED lighting systems were installed in August 2016, immediately prior to the start of the 2016-2017 school year. The schools, classrooms, and teachers to be included in the study were selected by the CFB facility staff in cooperation with district officials and the school principals. For each classroom selected for the LED trial, a corresponding base classroom was identified, which was of similar size and configuration to the LED classroom and had a typical incumbent fluorescent lighting system.

In the three classrooms that were included in the LED trial installation, each recessed fluorescent luminaire was replaced with a 2 ft by 4 ft Lithonia Lighting® BLT Series Tunable White LED luminaire from ABL. Luminaire locations remained the same. These luminaires offer tunable white lighting with a correlated color temperature (CCT) range of 3000 to 5000 K. The 4800 lm light output option was specified for the classrooms, and according to the manufacturer, this option results in a light output of 4993 lm at 45 W power for the 3000 K setting (111 lm/W), 4594 lm at 34 W power for 4000 K (135 lm/W), and 4819 lm at 39 W for 5000 K (124 lm/W). The luminaires were specified with a curved diffuser with linear prisms and with an nLight® nTune™ control interface.[4]

For control purposes, the luminaires in each classroom were grouped into rows that were parallel to the primary teaching / AV presentation wall. The luminaire row closest to that wall was designated as Row A; subsequent rows were designated as Rows B and C (and D for the BMS classroom), respectively.[5] Two push-button controllers were installed in each classroom from the nLight® nPODM series, as shown in Figure 4. For spectral power distribution (SPD) control, a four-button controller was used, with the buttons labeled GENERAL, READING, TESTING, and ENERGY. For light output control, an eight-button controller[6] was installed. Descriptions of the lighting system's programmed response for each control button are provided in Table 1.

Figure 4. Control station installed in each of the classrooms, with two nLight® nPODM controllers. The controller shown on the left provides SPD control and the controller shown on the right provides light output control. (Image credit: ABL.)

[4] Model number for the luminaires: 2BLT4 TUWH PROR 48L ADP NLT.
[5] The DES classroom had three rows of three luminaires, SES had three rows of four luminaires, and BMS had four rows of four luminaires, plus an additional luminaire near the entry that was labeled as Row E.
[6] Model number for the CCT controller: NPODM 4S EDUTW WH, for the light output controller: NPODM 4S DX WH.

The existing occupancy sensor in each classroom was replaced with an nLight® sensor for compatibility with the digital nLight® control platform. This ceiling-mounted sensor provides dual technology motion detection, combining passive infrared with microphonic technology to automatically switch luminaires off when no motion is detected after a defined time period, and to switch or keep luminaires on when motion is detected[7]. Other than the occupancy-based automatic on-off switching via the occupancy sensor, the light output and SPD control in the classrooms occurs manually.

Table 1. Descriptions for the control buttons installed in each classroom. The control configuration used is shown in Figure 4.

LIGHT OUTPUT CONTROL BUTTONS	
LABEL	**DESCRIPTION**
SCENE 1	FULL – All luminaires on at 100% setting
SCENE 2	AV MODE – Luminaire row A turned off; other rows dimmed to 40% setting
SCENE 3	PRESENTATION MODE – Luminaire Row A on at 100% setting; other rows dimmed to 50% setting
SCENE 4	DIM – All luminaires on at 10% setting
ON	All luminaires powered on at their previous setting
OFF	All luminaires powered off
UP ARROW	Light output of all luminaires increased by 5%
DOWN ARROW	Light output of all luminaires decreased by 5%
SPD CONTROL BUTTONS	
GENERAL	All luminaires set to 4200 K setting
READING	All luminaires set to 3000 K setting
TESTING	All luminaires set to 3500 K setting
ENERGY	All luminaires set to 5000 K setting

Figure 5 provides a photograph of the classroom at DES at each of the four SPD settings. Although the photographic process and the viewing of side-by-side images may tend to exaggerate differences, these images provide a sense of the visual differences that occur in the rooms with the different SPDs provided by the lighting systems.

[7] Model number for the occupancy sensor: NCM PDT 10 RJB.

Figure 5. **New tunable lighting in the classroom at DES. The four SPD settings are shown in clockwise order, beginning with the upper left photo: 3000 K (Reading), 3500 K (Testing), 4200 K (General), and 5000 K (Energy). The Scene 1 setting was used during the photographs, so all luminaires were on at full light output. (Photos courtesy of ABL.)**

3. Trial Installation: Results and Discussion

DOE evaluated the new LED systems in the study classrooms and the incumbent fluorescent systems in similar classrooms on October 26, 2016. A detailed evaluation was conducted of the LED system in the classroom at DES, consisting of

- a full illuminance survey at 15 measurement points for each of the four SPDs,
- vertical illuminance measurements on the whiteboard for each of the four scene control settings,
- a dimming evaluation at one measurement point where illuminance was measured for each of the 21 dimming control settings, for the 3000 and 5000 K settings,
- an evaluation of the color consistency between luminaires, where the color characteristics of six luminaires were measured at each of the four SPD settings, and
- vertical illuminance and SPD measurements at two measurement points at seated eye height for a person facing the interactive display, for each of the four SPDs, for Scene 1 (100% output setting) and for Scene 4 (10% output setting). These data were used for subsequent analysis of metrics related to circadian response.

Because the LED systems installed were very similar for all three classrooms, and due to time limitations, the evaluations of the systems in the SES and BMS schools were limited to an illuminance survey at the 4200 K (General) setting. For each of the base fluorescent classrooms, an illuminance survey was conducted, and the color properties of several of the fluorescent luminaires were measured. A calibrated[8] Konica Minolta® CL-500A spectrophotometer was used to measure SPDs and illuminances; relevant color metrics were calculated using the measured SPDs. All measurements were taken after dark in the two classrooms at SES, both of which have windows along one wall, to minimize any contributions from daylight. The other classrooms do not have windows.

Color consistency over the dimming range was evaluated for one BLT luminaire at the PNNL Lighting Metrology Laboratory[9] in Richland, WA.

3.1 Illuminance

Horizontal illuminances were measured at desktop height in each LED classroom and in each corresponding base fluorescent classroom. The number of measurement points in each room varied based on the room configuration, and ranged from 7 to 16. Table 2 shows the average horizontal illuminances and the maximum-to-minimum illuminance ratios (max:min) measured in each room.

To evaluate the suitability of the different control scenes for educational tasks such as lecturing and viewing of projected images, vertical illuminances were measured along the mid-height line of the interactive display at the left edge, center, and right edge for each of the four control scenes, for the 4200 K (General) control setting. Table 3 shows the average vertical illuminance for each of the four control scenes.

[8] CL-500A Konica Minolta® Illuminance Spectrophotometer (10002008) calibrated July 8, 2016
[9] Accredited to ISO/IEC 17025:2005 by the National Voluntary Laboratory Accreditation Program.

Table 2. **Measured horizontal illuminances and max:min ratios in the trial LED classrooms and the corresponding base fluorescent classrooms. The LED system descriptions shown are the CCT and percent light output levels of the control setting. Illuminances were measured at desk height, 30 inches above the floor.**

SCHOOL	SYSTEM	ILLUMINANCE (lx)	Max:Min Ratio
BMS	LED 4200 K, 100%	690	1.2
	Base fluorescent	860	1.1
DES	LED 4200 K, 100%	540	1.4
	Base fluorescent	770	1.5
SES	LED 4200 K, 100%	720	1.5
	Base fluorescent	460	2.0

Table 3. **Vertical illuminances on the interactive display for different control scenes in the LED classroom at DES. Measurements were taken for the General control setting (4200 K).**

CONTROL SCENE	DESCRIPTION (see Table 1 for details)	AVE. ILLUMINANCE (lx)
1	FULL	379
2	AV MODE	58
3	PRESENTATION MODE	314
4	DIM	34

3.2 Dimming Controls

As shown earlier in Table 1, the controls in each classroom included up and down arrows for manual control of the light output setting of all the luminaires in the room. To evaluate this control function, horizontal illuminance was measured at a single point in the room, first with all luminaires on at the full output setting (Scene 1), and then for each subsequent push of the down arrow control button. These measurements were completed for the 3000 and 5000 K CCT settings, and are provided in Table 4. The relative amount of dimming compared to the initial illuminance is shown in the column labeled, “% dim,” and illustrates that the control system was designed to provide linear dimming, with each step (i.e., each push of the down arrow button) reducing the illuminance by a nominal 5% of the full output illuminance. The relative change in illuminance between successive steps is shown in the column labeled, “% change,” which shows the change in light level from the current setting to the new setting when the down arrow is pushed.

These tables illustrate why a linear dimming strategy often does not match the user’s visual experience. In this application, since the lighting system at the full output setting provides about 700 lx, each subsequent push of the down arrow reduces the illuminance by about 35 lx. This means that for each of the first 10 times the down arrow is pushed, less than a 10% change in illuminance is achieved, as shown in the “% change” column. This change may be barely noticeable to the user. Later activations of the down arrow then produce much greater relative changes—the illuminance at the 17th button push decreases by about 25%, then 35% at the next push, then 50%, and finally off. This can confuse the user, as the dimming may not be perceived over the initial activations, then may seem quite dramatic towards the end.

These user experiences occur because of the approximately logarithmic response of the human visual system to changes in brightness.[10] Other dimming techniques adopt a non-linear strategy in the dimming rate; these techniques—sometimes referred to as power law or square law dimming—reportedly have received more favorable user ratings in past studies.[11]

Table 4. Illuminance changes during manual dimming in the LED classroom at DES. Measurements were taken for the Reading (3000 K) and Energy (5000 K) control settings. The "% change from prior" column shows the percent illuminance change relative to the immediately prior measurement, and the "% dim from initial" column shows the percent illuminance change relative to the initial illuminance (Dim 0 setting).

3000 K SETTING				5000 K SETTING			
DIM SETTING	ILLUMINANCE (lx)	% CHANGE FROM PRIOR	% DIM FROM INITIAL	DIM SETTING	ILLUMINANCE (lx)	% CHANGE FROM PRIOR	% DIM FROM INITIAL
0 (initial)	696	NA	NA	**0 (initial)**	680	NA	NA
1	663	4.7	4.7	**1**	645	5.1	5.1
2	628	5.3	9.8	**2**	611	5.3	10.1
3	593	5.6	14.8	**3**	573	6.2	15.7
4	562	5.2	19.3	**4**	538	6.1	20.9
5	527	6.2	24.3	**5**	502	6.7	26.2
6	491	6.8	29.5	**6**	466	7.2	31.5
7	457	6.9	34.3	**7**	433	7.1	36.3
8	419	8.3	39.8	**8**	397	8.3	41.6
9	381	9.1	45.3	**9**	360	9.3	47.1
10	345	9.4	50.4	**10**	326	9.4	52.1
11	306	11.3	56.0	**11**	288	11.7	57.6
12	266	13.1	61.8	**12**	250	13.2	63.2
13	225	15.4	67.7	**13**	213	14.8	68.7
14	189	16.0	72.8	**14**	179	16.0	73.7
15	151	20.1	78.3	**15**	148	17.3	78.2
16	121	19.9	82.6	**16**	119	19.6	82.5
17	93	23.1	86.6	**17**	90	24.4	86.8
18	61	34.4	91.2	**18**	58	35.6	91.5
19	30	50.8	95.7	**19**	28	51.7	95.9
20	2.2	92.7	99.7	**20**	2	92.9	99.7

3.3 Color Quality and Consistency

3.3.1 Comparisons of Installed Fluorescent and LED Luminaires

To evaluate the color quality of the incumbent fluorescent systems, SPD data were recorded for two luminaires in the base case classrooms in each of the three schools. For the trial LED systems, SPD data were recorded for six luminaires in the classroom at DES, at full light output (Scene 1 setting) for each of the four CCT control settings. From the SPD data, several chromaticity and color quality metrics were calculated; average values are reported in Table 5.

[10] DiLaura et al., The Lighting Handbook: Tenth Edition, 2011, Illuminating Engineering Society.
[11] See *Dimming: A technology-neutral definition* from ASSIST Recommends Volume 12 Issue 1, April 2013, Lighting Research Center at RPI.

The values measured for the fluorescent systems in DES and BMS are typical of T8 fluorescent systems, with color fidelity (R_f and color rendering index, or CRI) of about 80 and with color rendering of red objects (R_9) of greater than 0 but less than 10. The fluorescent system at SES had not been upgraded to T8, so it still had a system using T12 cool white lamps, with CRI of 62 and R_9 well below 0 (-111).

The LED system improved the color quality metrics slightly relative to the T8 fluorescent systems, with small increases in color fidelity and in red color-rendering. These changes were consistent across the four CCT settings. For SES, the LED system dramatically improved the color quality metrics relative to the base case T12 cool white system.

Color consistency was also evaluated for the six LED luminaires measured in DES, at full light output for each of the four CCT settings. For each CCT setting, the measured ranges of the six luminaires for both CCT and D_{uv} were well within the tolerances specified in ANSI C78.377.[12] The smallest range in CCT was at the 3000 K setting (range of 13 K), and the largest range in CCT was found at the 3500 K setting (53 K). The ranges of measured D_{uv} were less than 0.0009 at all CCT settings.

Table 5. Color quality metrics for the lighting systems in the CFB schools. The data for the fluorescent systems are the average values of two luminaires measured at each school. The LED system data are the average values of the six luminaires at DES, measured at full light output for each of the four CCT control settings.

LIGHTING SYSTEM	CCT (K)	D_{uv}	R_f	R_g	R_a (CRI)	R_9
Fluorescent – BMS	3691	0.0048	78	99	81	7
Fluorescent – DES	3813	0.0065	79	98	81	5
Fluorescent – SES	3890	0.0093	62	82	57	-111
LED 3000 K	3074	-0.0011	82	98	82	13
LED 3500 K	3487	-0.0023	82	97	84	19
LED 4200 K	4272	-0.0015	82	96	85	21
LED 5000 K	5145	0.0012	82	95	84	13

3.3.2 Color Consistency over the Dimming Range for the LED Luminaire

One sample of the LED luminaire model used in this project was evaluated at the PNNL Lighting Metrology Laboratory in Richland, WA. (This sample was not installed in the project.) The sample was tested at five different settings of light output, for each of the four SPD settings, using the methods previously developed for a DOE CALiPER report on this product category.[13] At each SPD setting, the luminaire was stabilized and then tested at the 100% output setting, then sequentially at the 75%, 50%, and 25% output settings, and finally at the minimum output setting that provided stable light output. Results of this testing are shown in Table 6. The CCT and D_{uv} values remained very consistent throughout the dimming range down to 25% output. While the variation was greater at the minimum setting, the light output values were very low at that setting, so that the greater color differences are less likely to be objectionable.

[12] *Specifications for the chromaticity of solid-state lighting products*, ANSI C78.377-2015.

[13] *CALiPER Report 23: Photometric Testing of White-Tunable LED Luminaires,* prepared by the DOE SSL program: https://energy.gov/sites/prod/files/2016/01/f28/caliper_23_white-tunable-led-luminaires.pdf

Table 6. Light output and color properties at different control settings.

OUTPUT SETTING (%)	LIGHT OUTPUT (lm)	CCT (K)	D_{UV}
100	2933	5072	0.0015
75	2181	5045	0.0015
50	1376	5022	0.0015
25	695	5003	0.0014
min	9	4948	0.0018
100	2923	4190	-0.0014
75	2203	4164	-0.0014
50	1505	4175	-0.0014
25	777	4166	-0.0014
min	9	4238	0.0000
100	3012	3500	-0.0022
75	2220	3507	-0.0022
50	1499	3502	-0.0021
25	766	3496	-0.0021
min	9	3287	-0.0017
100	2942	3059	-0.0012
75	2214	3049	-0.0010
50	1398	3042	-0.0010
25	665	3035	-0.0010
min	9	3014	-0.0011

3.4 Vertical Illuminance and Human Response Metrics

Interest in using tunable spectrum lighting has been driven in part by emerging evidence regarding the possible effects of lighting on human circadian and behavioral responses. Tunable lighting may enable the support of behavioral effects such as concentration and attention of students. It may also support circadian responses related to the hormone melatonin, which the human body produces in larger quantities during darkness. In classroom applications, circadian response considerations can include providing lighting that may support the suppression of melatonin during daytime hours and providing lighting that may minimize the suppression of melatonin during evening hours (when classrooms may be used by other community groups). Although the physiological mechanisms underlying these circadian effects are not yet fully understood, several metrics have recently been developed that weight the spectrum of light differently than metrics related to photopic human vision (such as lumens and illuminance). While the design for the CFB classrooms did not specifically cite any goals for these new metrics, the installation provided an opportunity for DOE to document how the tunable LED system affected the metrics in this application.

To evaluate how the tunable LED lighting systems installed in this trial installation produce variations in these new metrics, vertical illuminances and SPDs were measured at seated eye height for a person facing the front wall (interactive display wall), at two points in the DES classroom. Measurement point 8 was located in the center of the room, directly beneath a luminaire, and measurement point 13 was located 4 feet in front of point 8, between two luminaires. These illuminance and SPD measurements were completed for each of the four CCT settings, for both Scene 1 (all luminaires on at a control setting of 100%) and Scene 4 (all luminaires on at a control setting of 10%). Using these measurements, two metrics were calculated: equivalent melanopic lux (EML, with units of melanopic lux or m-lx)[14] and circadian stimulus (CS, unitless).[15]

Figure 6 shows the measured vertical illuminances and the calculated EML values for the two measurement points at the different control settings. The vertical illuminances were more than 30% higher at point 13 than at point 8. The mean vertical illuminance at each point varied by less than 7% from the maximum value across the SPD control settings; the mean vertical illuminance at point 13 for the 100% output control setting was 372 lx (range of 362 to 387 lx) and the mean at point 8 was 247 lx (range of 241 to 256 lx). This figure also shows that the EML values decreased consistently as the CCT rating associated with the SPD control setting decreased. For example, for point 13 at the 100% output setting, the EML value decreased from 283 m-lx at the 5000 K setting to 174 m-lx at the 3000 K setting, a reduction of 39%. Similarly, the EML value at point 8 was reduced by 39% for the 3000 K setting relative to the 5000 K setting.

As shown in Figure 7, the calculated CS values produced very different results relative to the changes across the four SPD settings. Whereas the EML values decreased consistently as the CCT rating decreased, the CS values at point 13 decreased from 0.34 for the 5000 K setting to 0.27 for the 4200 K setting, then increased to 0.37 for the 3500 K setting, then decreased again to 0.34 for the 3000 K setting. Notably, the CS value for the 5000 K setting was identical to the CS value for the 3000 K setting at this measurement point, while the EML value decreased by 39% between these two points. Figure 8 shows the SPDs associated with each of the control settings, as measured at point 13.

A full exploration of why the EML and CS values behave so differently for the different SPD settings is beyond the scope of this report, especially since these metrics were not part of the design strategy for the CFB classrooms. At the time of this report, neither of these metrics had been adopted by an authority such as the Illuminating Engineering Society (IES) or the International Commission on Illumination as an accepted way to model the effect of light on the human circadian response. However, one important point that emerges from the CFB data is that both metrics vary considerably based on the vertical illuminance at the eye, which in turn varies considerably based on the location in the room. Because the illuminances measured at the two points varied by more than 30%, the EML and CS metrics also varied significantly between point 13 and point 8.

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[14] The equivalent melanopic lux metric is based on a model published in “Measuring and Using Light in the Melanopsin Age,” Lucas et al., *Trends in Neuroscience*, January 2014. This paper includes an addendum with a calculation tool, but it does not recommend any criteria for EML levels. EML criteria have been published by the International WELL Building Institute, *The WELL Building Standard, v1 with Q3 2017 addenda*, 2017. The International Commission on Illumination has approved an alternative, SI-compliant method for evaluating melanopic content based on irradiance (CIE TN 003:2015, *Report on the First International Workshop on Circadian and Neurophysiological Photometry, 2013.*). DOE uses the method from the WELL Building Standard in this report.

[15] The circadian stimulus metric is based on a model of circadian physiology developed by the Lighting Research Center (LRC). For more information and a copy of the circadian stimulus calculator, visit the LRC Light and Health website: http://www.lrc.rpi.edu/programs/lightHealth/index.asp. Also see the journal paper “Light as a Circadian Stimulus for Architectural Lighting,” MS Rea and MG Figueiro, *Lighting Research & Technology,* November 2016.

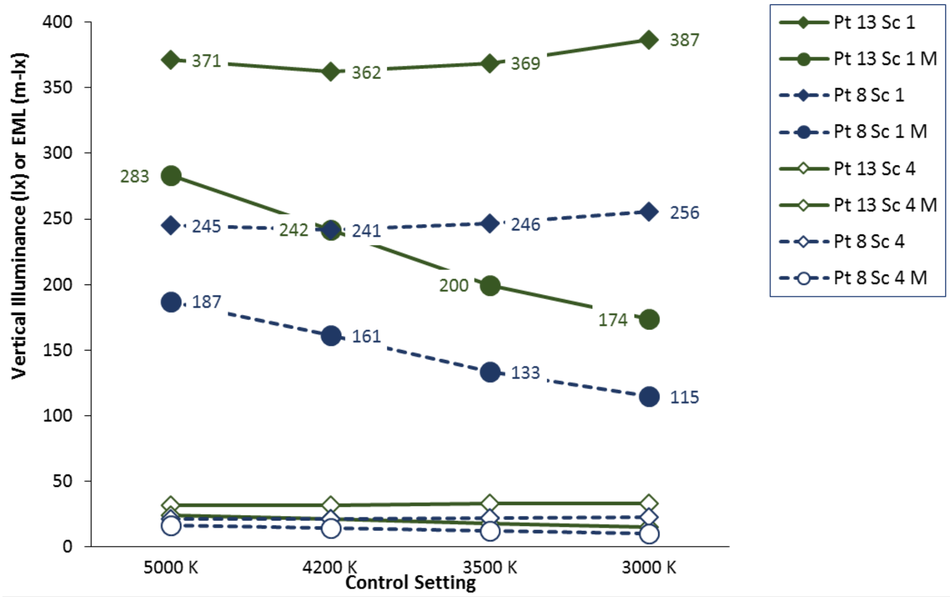

Figure 6. Vertical illuminance and EML values at two measurement points for each of the four SPD control settings at two output control settings (100% and 10%). Point 13 data are shown by the green (solid) lines, point 8 data are shown by the blue (dashed) lines. Vertical illuminance data are indicated with a diamond symbol and EML data are indicated with a circle. Filled symbols show the results for Scene 1 (100% output) and open symbols show the results for Scene 4 (10% output).

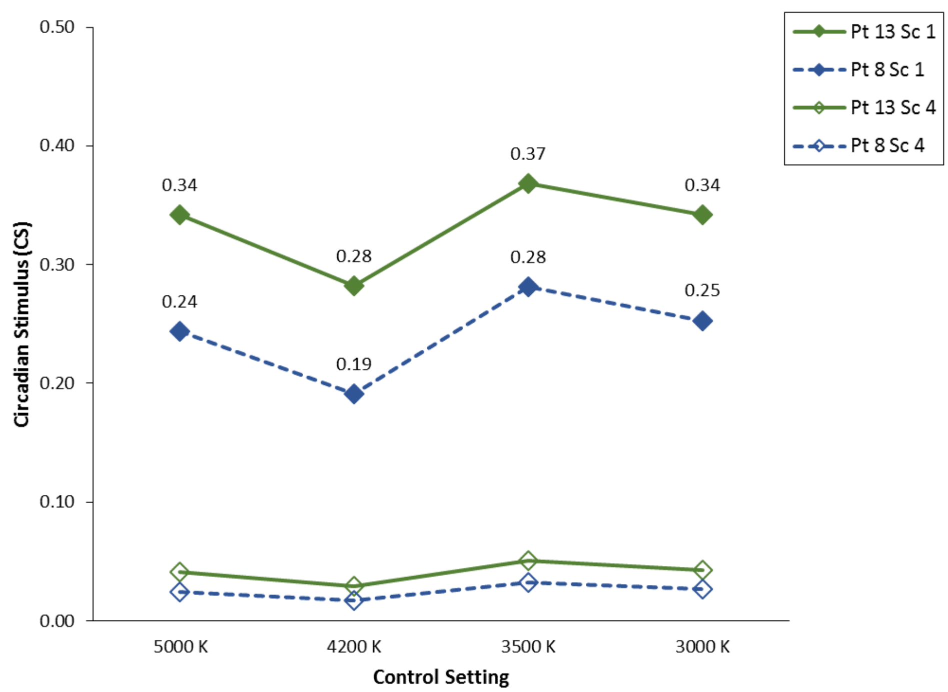

Figure 7. Circadian stimulus values at two measurement points for each of the four SPD control settings at two output control settings (100% and 10%). Point 13 data are shown by the green (solid) lines and point 8 data are shown by the blue (dashed) lines. Filled symbols show the results for Scene 1 (100% output) and open symbols show the results for Scene 4 (10% output).

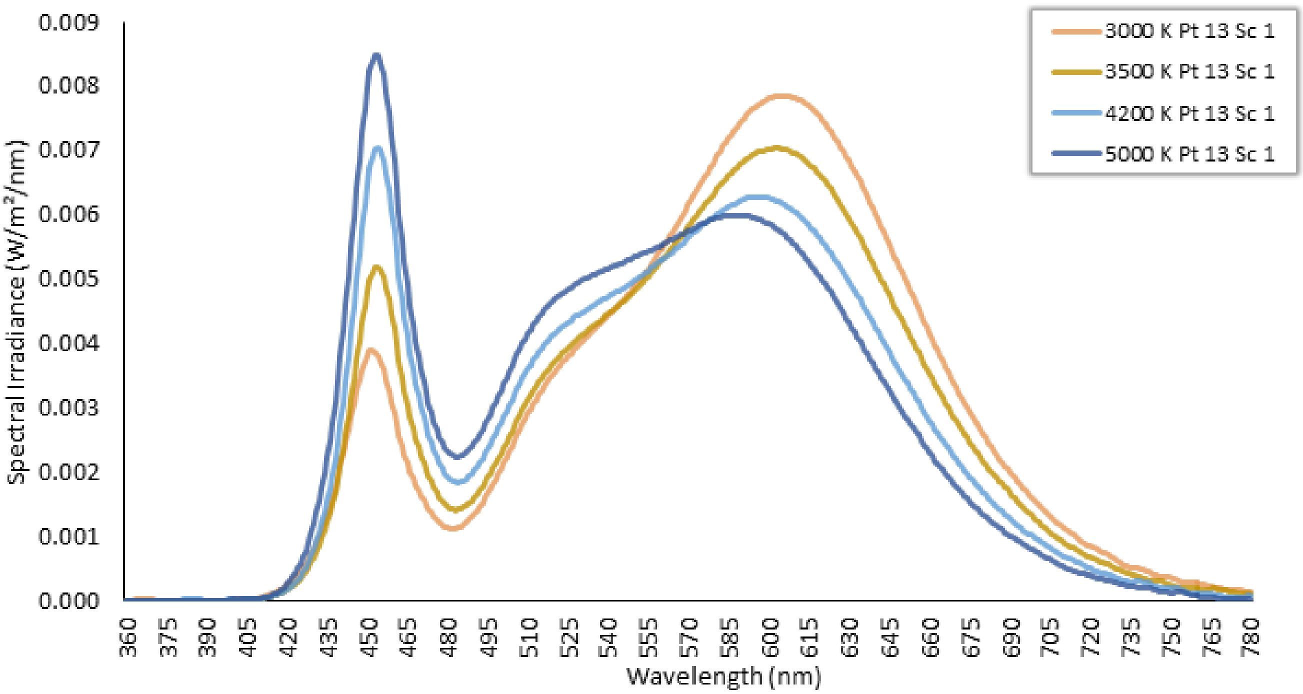

Figure 8. **SPDs for the four control settings, measured at point 13 for Scene 1 (100% output).**

3.5 Teacher Response

Two of the three teachers involved in the pilot study provided detailed feedback about the classroom lighting at the conclusion of the 2016-2017 school year. Their individual comments are summarized here.

3.5.1 Fifth Grade Math and Science Teacher at DES

This teacher had 49 students who were split between two groups; each group spent half the school day in the math and science room (with the pilot tunable LED lighting) and half the day across the hall in a language arts classroom (with the incumbent fluorescent lighting). After experimenting with different variations of the control settings early in the year, she decided which settings best supported her classroom activities and then used those settings most of the time. As described below, this resulted in Scenes 1 and 2 being used the most often, with the General and Reading SPD settings.

During the majority of the time with students, this teacher used Scene 1 (all luminaires on at the 100% control setting). She used Scene 2 (AV mode with front row of luminaires off and other room luminaires dimmed to the 40% output setting) occasionally for presentations, but felt that this scene was sometimes too dark overall. Whenever this teacher wanted to introduce a “breathing” period, a relaxation technique where one student opens and closes a breathing ball in front of the class while other students breathe in unison, she would set the lighting controls to Scene 4 (all luminaires dimmed to the 10% output setting). The breathing exercise was commonly used after recess or a special program, to help the students calm down when they seemed especially energized and active. As a rough estimate, this teacher used Scene 1 for 70% of the class time, Scene 2 for 25%, and Scene 4 for 5%. Scene 3 (presentation mode with front row of luminaires on at 100% setting; other rows dimmed to 50% setting) was not used.

For the SPD settings, the General setting (4200 K) was used for most class activities. The Reading setting (3000 K) was used on occasion for the breathing times and also was used whenever students were working on digital notebooks (iPads or Chromebooks), which occurred more frequently later in the school year than at the beginning. The Testing setting (3500 K) was used consistently during the standardized state tests, which were administered every 9 weeks throughout the year. The teacher used the Energy setting (5000 K) several times in the mornings, especially early in the school year, but she personally found that setting to be visually uncomfortable and stopped using it.

The primary difficulty encountered by this teacher was that the scene and CCT controls were located near the entry door at the back of the room, while the teacher's desk and the interactive display were located at the front of the room. The inconvenience of changing the controls limited the frequency with which the teacher made changes. She suggested that either a more convenient location for the wall controls, or a control application for a mobile device, may have encouraged her to more frequently change the scene or CCT. The dimming controls were almost never used by this teacher, again due to the inconvenience of the control location.

However, the control location also produced one of the teacher's favorite aspects of the system: The easiest way for her to change the setting was to ask one of the students seated near the controls to make the change. This increased student engagement, and as they grew familiar with the lighting and controls, the students would occasionally request certain settings. The students also learned to recognize the behavioral cues that the control settings indicated—the dimmed, warm setting became a cue that the teacher expected the class to be in their seats and quiet down.

3.5.2 Eighth Grade Science Teacher at BMS

This teacher remained in the science laboratory / classroom throughout the day while different groups of students came into the room. His experiences with the pilot LED tunable lighting installation were affected by his prior background in his classroom. In the previous 10 years with the fluorescent lighting, he estimated that he had migraine headaches four to six times per school year, which he believed were attributable to the fluorescent lighting. (He mentioned that the fluorescent lighting had flicker that was noticeable to him, and that he believed contributed to his headaches.) Because of the limited control over the fluorescent lighting system, which DOE had measured as producing about 860 lx on average at the lab desk surface, he felt that he had no real ability to change the lighting to accommodate his needs. The tunable LED system enabled the teacher to keep the lighting tuned to an intensity level that he believed suited the students and that helped him avoid a headache—he reported that this was the first school year in 10 years when he did not take at least one day off work due to a migraine.

The strategy used by this teacher with the lighting scenes was to generally set the lighting to Scene 4 (all luminaires on at 10% of full output), and then vary the level with the up/down controls to achieve the level needed for each class activity. In general, this meant only increasing the level by 5% to 20% from the initial 10% setting. (As discussed in Section 3.6.2, DOE verified through the monitoring system that the lighting in this classroom was rarely set above 20% of full output.) He used Scene 2 (AV mode) whenever he used the projector to show slides. Scene 1 (all luminaires on at 100%) was only used one time, when the students were using spectroscopes to observe the spectrum of light as part of a class exercise, and he never used Scene 3. He reported regular, daily use of the scene and intensity controls, setting the room to higher illuminances for lab and paper-based activities, and to lower levels when the students were using technology or for presentations.

In terms of the CCT settings, the teacher reported that he used the General setting (4200 K) during 90% of the class time, and he used the Testing setting (3500 K) during the other 10% of the time, either when testing was taking place or on occasion when he felt the warmer light might calm the students. He only used the Energy and Reading settings (5000 and 3000 K, respectively) one time, during the spectroscope exercise. To quote the teacher, “I find that Energy was not something that middle schoolers really needed.”

Like the fifth grade math teacher, this teacher felt that the tunable lighting system enhanced his ability to engage with students about the classroom environment. He would ask for student input on the control settings, and adjust the lighting based on their input. The teacher reported that many students commented how much they enjoyed coming to his classroom because the lighting was so much better than in their other classrooms.

In terms of suggestions for improvements, this teacher would have appreciated having the ability to program one of the scene buttons himself, since he almost always modified the light output from one of the pre-programmed scenes. He also noted that controlling the lighting from a mobile application would be helpful; because he runs his presentations from a mobile tablet, being able to also control the lighting from that tablet device would be very convenient for him. (The controller for this room was located at the front of the room, so this teacher did not have the concern mentioned in Section 3.5.1 about the remote location of the controller.)

3.5.3 Summary of Teacher Responses

The teachers involved in this pilot study who provided feedback to DOE responded positively to the lighting systems and controls. The adaptability of the lighting seemed to support the teachers’ engagement with the students, and overall contributed positively to the learning environment. Though very difficult to quantify, this empowerment of the teacher through improvements in lighting and lighting controls may be an important benefit that contributes to a better learning and working environment.

3.6 Energy and Economics

3.6.1 Overview of Energy Savings

Based on data provided to DOE by this Texas school district, energy for heating and cooling represents about 40% of the total energy use, followed by plug load at 28% and lighting at 24%. Lighting had historically been the second largest energy use, but the district’s past efforts at implementing energy efficient fluorescent lighting combined with the rapid increase in the use of computer equipment has resulted in plug load energy use exceeding that of lighting. However, with roughly a quarter of the district’s energy costs attributed to lighting, the potential for energy savings through the implementation of LED lighting is attractive.

For the pilot installation discussed in this report, which was a one-for-one replacement of the existing fluorescent luminaires, the luminaire power was reduced from 108 W for the T8 fluorescent system to 45 W for the tunable LED luminaires, a reduction of 58%. (The upgraded T8 systems in two of the classrooms evaluated were used as the base case reference conditions; the older T12 system in the third classroom was not used for comparison.) This reduction in luminaire power is partly attributable to the higher efficacy of LED luminaires relative to fluorescent luminaires, and partly attributable to the illuminance reduction of 20% in one of the classrooms and 30% in the other. The T8 fluorescent systems provided higher illuminances than those recommended by the IES[16]; the specifying engineer for the LED system selected the 45 W luminaire because it satisfied the desired illuminance levels.

While the reduction in luminaire power of 58% provides substantial energy savings, further savings will result from the scene and dimming controls provided as part of the LED system. These additional savings depend on each teacher's use of the controls and on the daily activities in each classroom. As discussed in the next section, these factors varied widely for the three classrooms and teachers included in the pilot installation, so that estimating the additional savings with any accuracy was not practical.

3.6.2 Analyses of Specific Classrooms

As part of the pilot installation, the luminaire/controls manufacturer installed a monitoring system to record the changes in the lighting control settings throughout the day. Although the system was designed to record both the SPD control setting and the intensity control setting, only the intensity control setting was successfully tracked. Using these tracked data, the daily changes in the lighting implemented by each teacher could be graphed. The results for a selected day in each classroom are shown in Figure 9, Figure 10, and Figure 11. These graphs illustrate that the individual teacher's usage of the lighting controls was very different.

Figure 9. Changes in percent output setting for a selected day in the classroom in BMS.

[16] DiLaura et al., The Lighting Handbook: Tenth Edition, 2011, Illuminating Engineering Society.

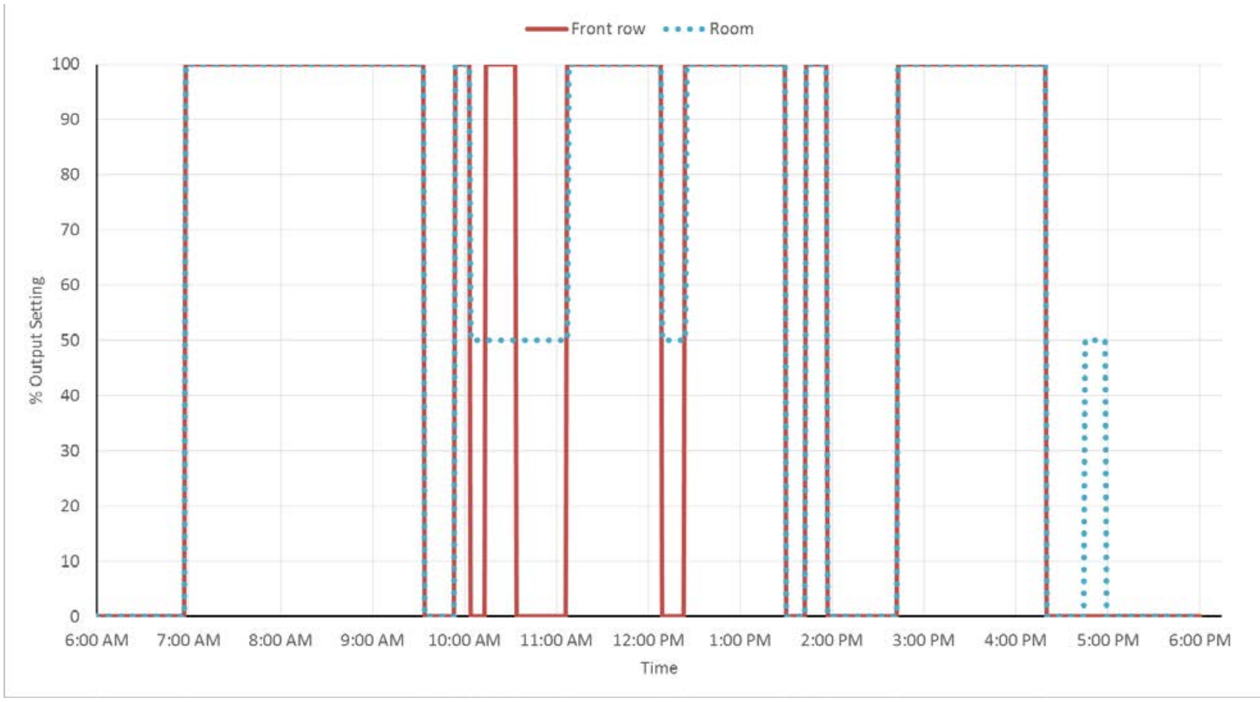

Figure 10. Changes in percent output setting for a selected day in the classroom in SES.

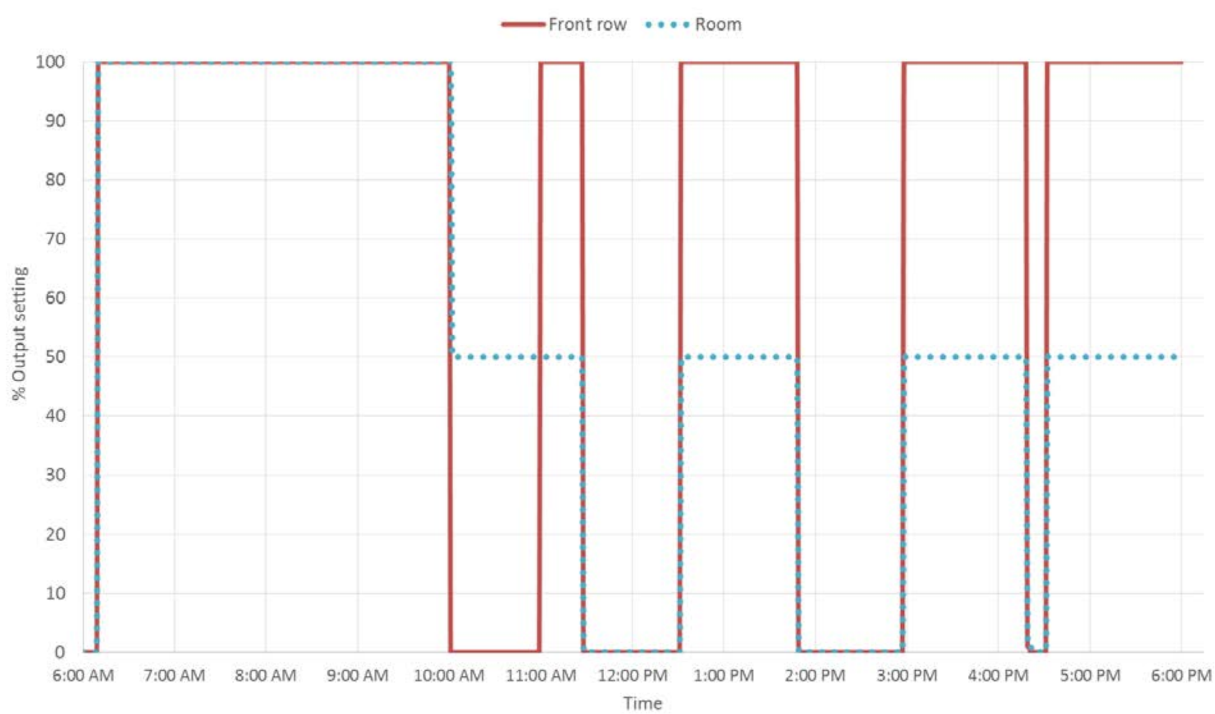

Figure 11. Changes in percent output setting for a selected day in the classroom in DES.

The differences among the output settings in the different classrooms during the school day are presented in Table 7, which shows that while the BMS teacher never had any of the classroom lighting operating above the

20% output control setting, the teacher at SES had the classroom lighting operating at full output for 7 hours that day, and used Scene 3 to operate the room lighting at 50% output for 1.5 hours. The DES teacher had the front row of the classroom lighting operating at full output for 8.5 hours, while the other room lighting was at the 50% dimmed setting for 5.5 hours. The data also reveal that while the BMS teacher regularly used the up/down control buttons to vary the light output from the levels set by the pre-set scene controls, the DES and SES teachers did not use the up/down controls. Data from other days reveal that the teachers' use of the scene controls varies somewhat day by day, presumably based on the specific activities occurring in the classroom.

Table 7. Hours at different light output control settings for a selected day (6:00 AM to 6:00 PM) for three classrooms. The front row of luminaires is shown separately from the rest of the room, since some of the control scenes varied the front row's output. Output settings that were not used during the selected day have a gray background for easier interpretation.

	BMS (hours)		SES (hours)		DES (hours)	
Output	**Front Row**	**Room**	**Front Row**	**Room**	**Front Row**	**Room**
Off	2	2	5	3.5	3.5	2.5
10-20% full	10	10	0	0	0	0
50% full	0	0	0	1.5	0	5.5
Full	0	0	7	7	8.5	4

Although these individual differences present difficulties for allowing the sort of generalizations desired for energy estimations, they illustrate a primary benefit of tunable lighting systems—these systems give the teacher additional flexibility to meet their own and their students' needs and preferences.

3.6.3 The Economics of a Color-Tunable Classroom System

Although the LED lighting system installed as part of this project provides the potential for significant energy savings compared to the incumbent fluorescent system, the reality is that a fixed-color LED system with the same scene and dimming controls would provide similar energy savings. The color tuning capability of an LED system provides no additional energy savings relative to a non-color tuning system; in fact, in some cases a color-tunable system may provide less savings, since a given tunable luminaire may be less efficacious than a similar non-tunable model.[17] Because of this, any additional cost required for a color-tunable system needs to be justified based on benefits beyond energy savings.

Based on the positive results from the pilot installation of a color-tunable LED system, the CFB district sought pricing estimates to renovate an entire school with the color-tunable LED system, and for comparison also received pricing estimates for a renovation that included a similar LED system that was not color tunable. Although the details of the estimates are not public, the cost for the color-tunable system was over 25% more than the cost of the non-color tunable system, with no difference in energy savings. As of this report, the district was not convinced that the benefits of the color tuning capability justified the additional costs compared to dimming and scene-setting alone. As research data become available documenting the possible benefits of color tunable lighting, such as improvements in student learning outcomes and behaviors, and increases in teacher satisfaction and retention, CFB will reevaluate this option as a valid environmental improvement to positively impact student performance.

[17] For further information, download the *CALiPER Report 23: Photometric Testing of White-Tunable LED Luminaires* prepared by the DOE SSL program: https://energy.gov/sites/prod/files/2016/01/f28/caliper_23_white-tunable-led-luminaires.pdf.

4. Conclusion

This evaluation of a pilot installation of color-tunable LED lighting systems in three classrooms provided a number of insights into the use of this technology in a real-world setting. Several of the key results and lessons learned are summarized below.

4.1 Key Results

Key results from the trial installation included the following:

- The reduction in input power for the tunable-white LED lighting system used in the three classrooms was estimated to be 58% relative to the incumbent fluorescent system. This reduction in luminaire power is attributable to the higher efficacy of the LED luminaires and a reduction in illuminances, which previously exceeded IES-recommended levels.
- The dimming incorporated into the scene controls and separate up and down dimming controls furthered the energy savings in each classroom. While the individual teacher's usage of the controls varied widely, in each case the lighting consistently operated with all or some of the luminaires turned off or dimmed for portions of the school day.
- The LED lighting systems were installed and commissioned with very few difficulties, and any issues with initial performance were quickly resolved.
- The three teachers involved used the scene controls regularly during the school day, but used the SPD controls infrequently.
- Illuminance levels in the classrooms at maximum output met or exceeded IES recommendations for the typical visual tasks, with both the new LED and the incumbent fluorescent systems.
- Color consistency for the tunable white LED luminaires used in the classrooms was very good among luminaires and good over the dimming range, with minor variations in CCT and D_{uv}.
- The two teachers interviewed by DOE appreciated the ability to tailor the lighting to different classroom needs, and felt that the lighting and controls allowed the students to be engaged in choosing the settings for various classroom activities. Both teachers stated that the lighting system improved the overall learning environment.

4.2 Future Improvements for Classroom Lighting Systems

Lessons learned from this project that provide insight for possible future improvements for implementing tunable-white classroom lighting systems and their associated controls included the following:

- Although teachers are probably unfamiliar with lighting metrics related to color quality such as CCT, labeling lighting control settings with more familiar terms may provide barriers to full usage of the controls. In this project, labels such as “Reading,” “Testing,” and “Energy” seemed to be taken literally by the teachers, and they did not seem to use those control settings for other classroom functions that did not match the labels. The “General” control setting served as the default setting.

- Use of lighting controls may be enhanced when the control locations are convenient for the teacher. The control locations for this pilot retrofit project were constrained by the existing wiring, and where the control locations were more easily accessed by the teacher, the settings (specifically the dimming level) were varied more regularly than when the controls were less convenient for the teacher to access.
- Energy savings from tunable classroom systems results from the switching and dimming functionality of the scene control settings and the manual dimming controls; the ability to vary the color temperature does not necessarily provide additional energy savings. Because color-tunable systems are at present more costly than fixed-color LED systems (which can still provide full scene and dimming control), an economic argument cannot be based on energy alone. Like other classroom upgrades (better furnishings, better instructional technology, better air quality, etc.), the justification for color-tunable systems needs to include non-energy benefits related to a better learning and working environment, possibly linked to student learning outcomes, teacher satisfaction and retention, and human health impacts. The difficulty in documenting and assigning economic value to these potential non-energy benefits poses a major challenge for color-tunable lighting systems in classrooms and other applications.

4.3 Summary

This report presented the results from a trial installation of color-tunable LED lighting systems in three classrooms in Carrollton, TX, where DOE documented the performance of the LED lighting systems as part of a GATEWAY evaluation. The three classrooms included in the LED lighting system installation and evaluation were a fifth-grade math and science classroom, a fourth-grade reading and language arts classroom, and an eighth-grade science laboratory. In each case, there was a very similar classroom located nearby that retained the incumbent fluorescent lighting system, and that was used as a base case reference for comparison to the LED lighting system.

The lighting control system provided the ability to vary the SPD of the lighting across four pre-set conditions, associated with nominal CCTs of 3000 K, 3500 K, 4200 K, and 5000 K. The controls also provided for pre-set scene controls to vary the on/off status and dimming level of different luminaire zones within the room, to better support classroom functions such as AV presentations and student speeches.

Beyond the key results and lessons learned summarized above, this project also provided insight into the use of color-tunable LED lighting to achieve non-energy benefits. The combination of spectral tuning and dimming in the classrooms provides greater opportunity to vary lighting parameters that may affect circadian and behavioral responses for students, teachers, and other users of the classrooms, relative to the fluorescent systems. While documenting these circadian and behavioral effects was beyond the scope of this project, the tunable LED systems may be adaptable to reinforce the desired outcomes, should scientific consensus emerge that supports specific SPD and intensity settings for related effects.