Lighting Quality And Lighting Measurement Assessment
Paper #74

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ABSTRACT

The 1999 Non-Residential New Construction (NRNC) Baseline Study, conducted on behalf of the California Board for Energy Efficiency, estimated the energy savings relative to the 1995 Title 24 for 667 newly constructed nonresidential buildings in California. According to the study results, 72% of the total energy savings were attributable to lighting power savings. These results are significant but raise several questions:

- **Measurement Error**: Are there systematic errors in the lighting surveys? Are surveyors undercounting the number of fixtures? Do random errors in fixture counts and wattage estimates tend to cancel each other?
- **Lighting Quality**: Why are certain buildings achieving high lighting energy savings? Is lighting quality being sacrificed? Or is the lighting design superior in efficiency?

In order to have confidence in the survey results and to better understand the implications of reduced lighting energy use, a follow-on study was conducted.

The Lighting Power Density (LPD) measurement error task carefully re-surveyed a sample of Baseline Study sites to get a better understanding of lighting power and savings by area usage. The lighting quality assessment task involved both light meter measurements of illuminance and occupant satisfaction surveys in high, medium and low LPD sites. We present our results by comparing lighting power densities, illuminance measurements and behavioral outcomes. By comparing the occupants' opinions with the LPDs and illuminance measurements, we are able to judge the presence or absence of a consistent relationship.

Introduction

The study described in this paper was designed to provide an assessment of lighting audit measurement error and lighting quality in three specific contexts: in open plan offices, in retail stores and in school classrooms.

The first part of the study calculated the lighting power density measurement error associated with previous on-site data collection activity to determine if there was a significant systematic bias in the counting of the number of luminaries, estimating the wattage, or measuring the floor space.

The second part of this study investigated the correlation between the lighting power density (LPD) of a lighting installation and the lighting quality provided by the electric lighting. Lighting quality was assessed through light level measurements and a survey of occupant satisfaction.

The study is an extension of the work done for the Non-Residential New Construction (NRNC) Baseline Study and its database of 667 newly constructed buildings (RLW 1999). The NRNC Baseline Study, conducted on behalf of the California Board for Energy Efficiency, estimated the energy savings relative to the 1995 Title 24[1] efficiency baseline for 667 newly constructed nonresidential buildings in California. According to the study results, 72% of the total energy savings, when compared to the 1995

[1] Title 24 refers to California's Building Energy Efficiency Standards, a statewide energy code that regulates, for nonresidential buildings, the efficiency of building envelope, lighting, and mechanical systems. The official name is *California Code of Regulations, Title 24-, Part 2, Chapter 2-53.*

Title 24 Standards, were attributable to lighting power savings (64% when compared to 1998 Standards)[2]. This amounted to a 9.5% reduction in total energy use (4% when compared to 1998) (RLW 2000). These results are very significant but they raise several questions:

- **Measurement Error**: Are there systematic errors in the lighting surveys? Are the surveyors undercounting the number of fixtures or the square footage? Or are there random errors in the surveys, which tend to cancel each other?
- **Lighting Quality**: Is lighting quality being sacrificed for energy efficiency? Are occupants dissatisfied with the lighting quality in buildings with lower lighting power densities? Are occupants' satisfaction levels sensitive to measured LPDs or illuminance levels?

In order to verify the reliability of the NRNC Baseline Study survey results and to better understand the implications of reduced lighting energy use, this follow-on study was conducted to answer these questions. In this project we re-surveyed a sample of the sites from the original NRNC Baseline Study. The sample was selected to include sites with low, medium, and high LPD, for various building types and sizes. The major findings of this study are presented in two sections: Lighting Measurement Error and Lighting Quality Assessment.

Methodology

Sample

A sample of 75 buildings of the Baseline sites was planned for this study. To address both study objectives, the sample needed to represent sites with low, medium, and high LPD and be matched as closely as possible on other characteristics, especially building type and size.

The sampling frame was the 562 sites in the original NRNC Baseline sample in three building types, office, retail and schools. The fourth building type of the Baseline Study, public assembly, was excluded from this study because of the wide diversity of buildings in this category. **Table 1** shows the number of sites in each category from the original NRNC Baseline sample.

Table 1. Number of Available Sites by Building Type

Bldg. Type	No of Sites
Office	231
Retail	162
School	169
Total	562

The sample was stratified to obtain a balance of buildings with low, medium and high LPD, so that we could get a meaningful range for purposes of lighting quality assessment. **Table 2** shows the cut-points selected for defining these three LPD levels.

Table 2. LPD Categories

	LPD		
Bldg. Type	**Low**	**Medium**	**High**
Office	<1.0	1.0 - 1.75	>1.75
Retail	<1.5	1.5 - 2.5	>2.5
School	<1.0	1.0 - 1.75	>1.75

With these restrictions, the target population for this project was 317 small and medium sized sites included in the office, retail, and schools segments of the original Baseline Study. The population

[2] Energy savings were calculated from on-site building surveys, detailed energy simulations, and utility billing data.

was stratified by building size and lighting power density (LPD). Seventy-five sites were selected following the stratified sampling plan shown in **Table 3**.

Table 3. Population and Sample

Type	Size (ksf)	LPD (W/sf)	Population	Sample
Office	0 - 50	0 - 1	19	3
Office	0 - 50	1 - 1.75	50	10
Office	0 - 50	> 1.75	9	4
Office	50 - 100	0 - 1	10	2
Office	50 - 100	1 - 1.75	27	2
Retail	0 - 50	0 - 1.5	15	7
Retail	0 - 50	1.5 - 2.5	46	8
Retail	0 - 50	> 2.5	13	4
Retail	50 - 100	0 - 1.5	18	2
Retail	50 - 100	1.5 - 2.5	18	2
Retail	50 - 100	> 2.5	9	2
School	0 - 50	0 - 1	8	1
School	0 - 50	1 - 1.75	47	10
School	0 - 50	> 1.75	12	5
School	50 - 100	0 - 1	2	1
School	50 - 100	1 - 1.75	14	2
Total			317	65

Ten sites were dropped from the measurement error analysis because of mismatches in survey areas or because of changes to the lighting system that prevented meaningful comparisons between the original survey and the re-survey. Seven sites were dropped from the lighting quality analysis due to incomplete measurements or survey responses. **Table 4** presents the final sample by building type for each component of the study.

Table 4. Final Sample

Bldg. Type	Lighting Measurement Error	Lighting Quality Assessment
Office	21	25
Retail	25	22
School	19	21
Total	65	68

Screening Procedure

The sampling procedure ensured that the sites selected for the study were screened to meet the specific qualification requirements of the study. Sites were eliminated if they had experienced any of the following conditions:

- Change to the lighting system,
- Change in occupancy,
- Change in space configuration or size.

Once the sites were selected and screened an on-site data collection visit was scheduled.

Lighting Measurement Error

The lighting measurement task carefully re-surveyed a sample of Baseline Study sites to calculate the measurement error and an error band for the results. A data collection protocol was developed for the on-site surveys to ensure that consistent and reliable measurement and counts were made at each site. Complete counts of light fixtures were made and floor areas were measured. Samples of the light fixtures were accessed by physically opening them to verify specific lamp and ballast information and to determine the fixture wattage.

Since the purpose of the fieldwork was to get an independent recount of the lighting system, the surveyors were intentionally not given the complete information from the original database. Instead, space type, space area, and fixture description at the aggregate level were provided to the surveyors to ensure that they were assessing the targeted buildings.

Track lighting and task lighting data were collected to capture the impact of all light sources. For retail spaces with track lighting, surveyors were explicitly directed to record the length of track and the number of track heads to better describe the prevalence of track lighting. For office spaces information on task lights was collected to test assumptions about task lighting.

Lighting Quality Assessment

Lighting quality was assessed by correlating lighting power densities and illuminance measurements to occupants' attitudes towards lighting comfort and behavioral outcomes. The premise for a behavioral outcome is simply that, in functional spaces such as those of interest in this study, good quality lighting allows the occupants of the space to perform their tasks with comfort. Any lighting installation that inhibits occupants from performing their intended tasks and/or causing them discomfort is likely to be considered poor quality lighting.

To assess the behavioral outcome of lighting quality, data on occupants' attitudes toward lighting quality were collected using a simple, nationally normalized, lighting quality assessment questionnaire (Boyce & Eklund 1996).

The lighting quality measurements and the criteria to which they were compared are shown in **Table 5**. The normative data of the "percent of respondents finding the lighting comfortable" quantifies the users' reactions to average lighting installations in use today. The criteria for passing are acceptable thresholds as determined by the cited source, and can vary by space type.

Table 5. Lighting Quality Measurements and Criteria for Passing

Quantity	***Measurement Method***	***Criterion to pass (source)***
% finding the lighting comfortable	*lighting survey questionnaire*	*>70%* *normative data* (Boyce & Eklund 1996)
average illuminance	*illuminance measured at sample points*	*variable according to situation (IESNA 1993)*
illuminance uniformity	*min./avg. illuminance measured at sample points*	*>0.8* *(CIBSE 1994)*
LPD (W/sf)	*calculation from total lighting fixture count and floor area measurement*	*variable according to situation (California Code 1998)*

Illuminance Measurements. Photometric measurements were made using a hand-held light meter for horizontal and vertical illuminance at a sample of locations in each space.

The approach used the concept of "cubic" measurements. Cubic measurements were based on a hypothetical six-faced cube positioned four feet off the ground, with measurements made of the illuminance falling on each of the six faces. To make the actual measurements, surveyors held the light meter at chest height and turned in 90° increments to take the four vertical measurements (front, left, back, right). Standing facing "front" the surveyors held the meter at arms length, also four feet off the ground, to get the horizontal top and bottom measurements. The top measurement was for horizontal surface illuminance in the general work area, the four side readings describe vertical surface illuminance and the differences between the four orientations, and the downward measurement described floor surface reflected illuminance.

The "top" cubic measurement was used for all horizontal measurements. Additional horizontal desktop measurements were taken in offices and classrooms with the light meter placed flat on the horizontal work surface. Vertical measurements were taken with slightly different criteria for the three space types as described below.

The minimum, maximum and mean values were calculated for each of the measurements within a space. Illuminance uniformity was calculated from the illuminance measurements as minimum horizontal illuminance divided by average horizontal illuminance. A value of 1.0 means that there is no variability in the measured illuminance.

For offices, illuminance measurements were made at representative, but usually vacant, workstations or desks in each office, so as to minimize disruption to the occupants. At each workstation, the illuminance measurements were made at six locations. Five horizontal measurements on the desk surface were taken: two each on either side of the computer, and one at the keyboard. A "top" cubic measurement was taken four feet off the floor at approximately the location of an occupant sitting at the desk.

Vertical measurements were taken with slightly different criteria for the three space types. For offices, the vertical cubic measurements were taken at the same location as the "top" measurement described above. One vertical measurement was taken on the plane of the computer screen.

For retail applications the lighting measurements were taken in the merchandise and circulation areas. The cubic illuminance measurements were taken at a minimum of eight different locations. In stores where extensive shelving was used to display merchandise, illuminance readings were taken on the vertical plane of the merchandise at various heights. Additional vertical measurements were made on the upper walls above merchandise display with the light meter held flat against the wall.

For classrooms, the surveyors selected a typical but usually vacant room for the lighting measurements. Lighting measurements were made at the students' desks and at the teacher's work area, including whiteboards and blackboards. The student desks were treated in the same way as the desks in the offices. Vertical illuminance measurements were taken on the walls as well as on the plane of the work surfaces including blackboards, whiteboards, computer screens and TV monitors.

Because most schools have some daylight that cannot be factored out of satisfaction responses, illuminance measurements were taken with and without the daylight influence to identify any significant differences. Seventeen of the spaces had measurements taken with and without daylighting.

Surveyors first took illuminance measurements with the lights on and the blinds open. To minimize the daylighting contribution to classroom illuminance, the surveyors drew the blinds and measured the contribution of the electric lights only. When the blinds could not be drawn, the surveyors took illuminance measurements with the lights off to account for the daylighting contribution only.

Occupant Satisfaction Survey. The occupants' attitudes toward lighting quality were collected using a short, self-administered, confidential questionnaire. The occupant satisfaction questionnaire is based on the Office Lighting Survey developed as part of the Commercial Lighting Evaluation Toolkit (Boyce & Eklund 1996). This survey is intended for use in multi-occupant offices where ideally at least twenty people occupy the office and are exposed to the same lighting installation. This survey has been shown to be reliable and valid for its purpose, and has been administered to over 1,200 office workers in thirteen office buildings of various ages.

The questionnaire took about five minutes to complete. A different, but similar, questionnaire was used for each of the three space types. Surveyors distributed the questionnaires after selecting the space to be measured. The questionnaire was distributed to all occupants within the space to be measured as well as those in spaces with very similar lighting conditions.

The results from the questionnaire were tallied and are presented in **Table 6**. The questions in bold text in the table are those summarized in this paper.

The questionnaire for retail applications was similar to the office lighting questionnaire but with additional questions concerning the appearance of the merchandise, which is a major concern to retailers. The retail questionnaire was aimed at large open retail applications lit by one predominant lighting system. The survey was distributed to all available staff. Customers were not given the surveys due to the difficulties of getting a company's authorization to survey customers; also, we believed we would get more informed opinions about the lighting quality from the employees who occupy the space all day long.

The questionnaire used for classrooms was similar to the office and retail lighting questionnaires but with additional questions evaluating lighting quality on the students' desks and the teaching surfaces. The survey was designed to evaluate a typical classroom, not specialized areas such as drama or science classrooms. The survey was distributed to all teachers who occupied classrooms similar to the one where the lighting measurements were made. Students were not surveyed due to concerns about gaining access to the students. We also felt that the teachers would provide better, objective responses.

Table 6. Lighting Quality Responses for Offices

Question	Average % agree	Range of Responses
Overall, the lighting is comfortable.	90%	71% to 100%
The lighting helps me to focus on my work.	72%	25% to 100%
The lighting is uncomfortably bright.	12%	0% to 36%
The lighting is uncomfortably dim.	6%	0% to 33%
The light fixtures themselves are too bright.	7%	0% to 45%
There is too much light in some areas; not enough in others.	31%	0% to 67%
The lighting causes deep shadows.	12%	0% to 40%
Reflections from the light fixtures sometimes hinder my work.	22%	0% to 67%
Skin tones look unnatural under this lighting.	20%	0% to 55%
It is difficult to distinguish shades of color under this lighting.	6%	0% to 18%
The lights sometimes flicker or hum annoyingly.	13%	0% to 50%
*How does the lighting compare to similar workplace in other buildings.**	4.85	4.00 to 6.67
Number of respondents/site(n)	8	3 to 15

*Provided on a scale of 1-7 with 1 = worse, 4 = about the same and 7 = better

Research Constraints

While we are confident in our results, and believe it to be a significant lighting assessment for buildings in California, there are obvious limitations associated with the study. The research plan was constructed under the following constraints:

One or two people visiting a site carried out the field evaluation. These people were trained surveyors, but were not lighting experts, and therefore required a specific protocol on how to carry out the evaluation. The uniform protocol, while serving the majority of the sites, might result in inadequate measurements for unique sites.

The time and budget available to carry out the field evaluation were limited, resulting in a limited number of sites and the use of timesaving strategies while on site.

The instrumentation for lighting measurements was limited to an illuminance meter. More sophisticated equipment may have produced better measurements.

Disruption to the building occupants was minimized. Therefore lighting measurements had to be made in a manner and in areas that were the least disruptive to the occupants.

The site visits were made during the daytime, which meant that the lighting at the time of the lighting measurements, at many sites, included contributions from both electric lighting and daylighting. All efforts were made to minimize the effect of daylighting on the space (from either windows or skylights). However, it was not always possible to completely eliminate the daylighting impact. For these situations, the contribution of daylighting was determined in a quick and relatively simple manner.

The questionnaires used in the retail stores and the school classrooms had not been tested in previous studies. Rather, they were derived from the office lighting survey.

Results

Lighting Measurement Error

The general conclusion is that measurement error is not a material issue in interpreting the results of the Baseline Study. This study has shown that the original lighting measurements were substantially accurate. Additionally, we conclude that field survey research entails a certain degree of measurement error. Even after all of this analysis, we are unable to state with absolute certainty the sources of errors or the correct answer. Rather, we rely on the statistical margins of error to reassure us that the original survey data is accurate for all practical purposes. Users must be aware of the limits to accuracy in using this type of survey data for analysis purposes.

This validation study gave consistent results in all three building types, the two size categories, and the three LPD categories. In each case, the re-survey results indicate that the original lighting power density results are slightly low. The difference is small, less than 5% overall, and not statistically significant. According to the re-survey, in all cases the original wattage and area survey results were consistently slightly high.

Table 7 summarizes the key results. The three right-hand columns show the ratios between the resurvey findings and the original survey findings (ratios greater than 1.0 indicate higher values in the resurvey than in the original survey data). The first row shows the results for all buildings taken together. In every category, the average LPD was found to be slightly lower in the original survey than in the re-survey. The average Watts of connected lighting from the original survey compared to the re-survey tended to be slightly larger. The average area per building in the original survey was somewhat larger than the average area per building in the re-survey.

Table 8 shows key ratios for wattage, area and LPD (Watts per square foot) derived from the results. Our calculations indicate that the lighting power density has been measured with a high degree of statistical accuracy. In other words, the confidence intervals are narrow. These confidence intervals reflect the variation that might be expected from one sample to another from the target population.

Table 7. Key Measurement Results for All Categories of Buildings

Category		Resurv. LPD	Orig. LPD	Resurv. LPD vs Orig. LPD	Resurv. Watts vs Orig. Watts	Resurv. Area vs Orig. Area
All Buildings		1.419	1.362	1.042	0.989	0.949
Type	Office	1.022	0.989	1.033	0.964	0.933
	Retail	1.644	1.599	1.028	0.975	0.949
	School	1.332	1.230	1.083	1.046	0.966
Size	Small	1.451	1.387	1.046	1.016	0.971
	Medium	1.398	1.345	1.039	0.971	0.935
LPD	Low	1.404	1.224	1.148	1.011	0.881
	Medium	1.332	1.324	1.006	0.989	0.983
	High	1.996	1.941	1.028	0.955	0.929

Table 8. Key Ratios & Measurements, All Building Types

Ratios & Measurements	Estimate	Err Bnd	Low	High	Rel Prec
Resurv. Watts vs. Orig. Watts	0.989	0.042	0.947	1.031	0.042
Resurv. Area vs. Orig. Area	0.949	0.030	0.919	0.980	0.032
Orig. LPD	1.362	0.104	1.258	1.465	0.076
Resurv. LPD	1.419	0.093	1.326	1.512	0.066
Resurv. LPD - Orig. LPD	0.058	0.071	-0.014	0.129	

Lighting Quality Assessment

Our analysis shows that there is virtually no correlation between lighting power density, illuminance uniformity, and occupant satisfaction, at least within the range of conditions observed in our surveys. We analyzed the data by comparing occupant satisfaction ratings to LPD (in Watts/sf), illuminance (in footcandles) and illuminance uniformity (minimum illuminance vs. average illuminance).

Figure 1 and **Figure 2** show that there is no correlation between LPD and overall occupant comfort. This contradicts an expectation by some that more lighting is better and less lighting means a sacrifice in comfort.

Illuminance uniformity is a quantity that describes lighting distribution. Unevenly distributed lighting can result in occupant discomfort. However, **Figure 3** shows occupants' overall comfort and satisfaction compared to measured illuminance uniformity, showing no clear correlation between comfort and lighting uniformity in these buildings.

The comparison shown in **Figure 4** indicates that occupants' perceptions of lighting uniformity do not typically correspond to actual measured uniformity. **Figure 5** presents the measured illuminance uniformity compared to LPD.

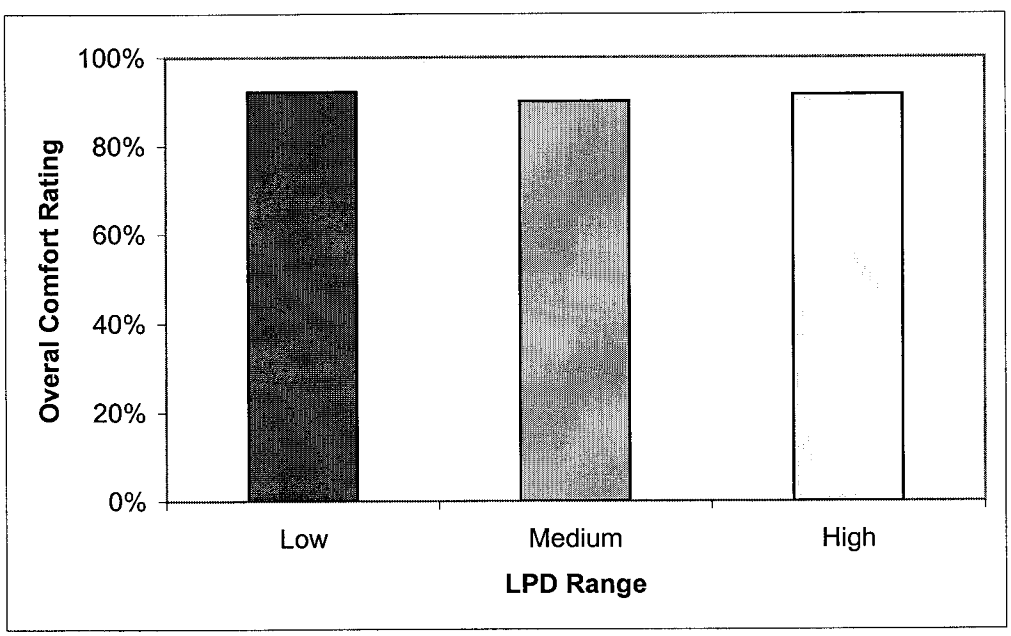

Figure 1. Overall Comfort vs. LPD Range

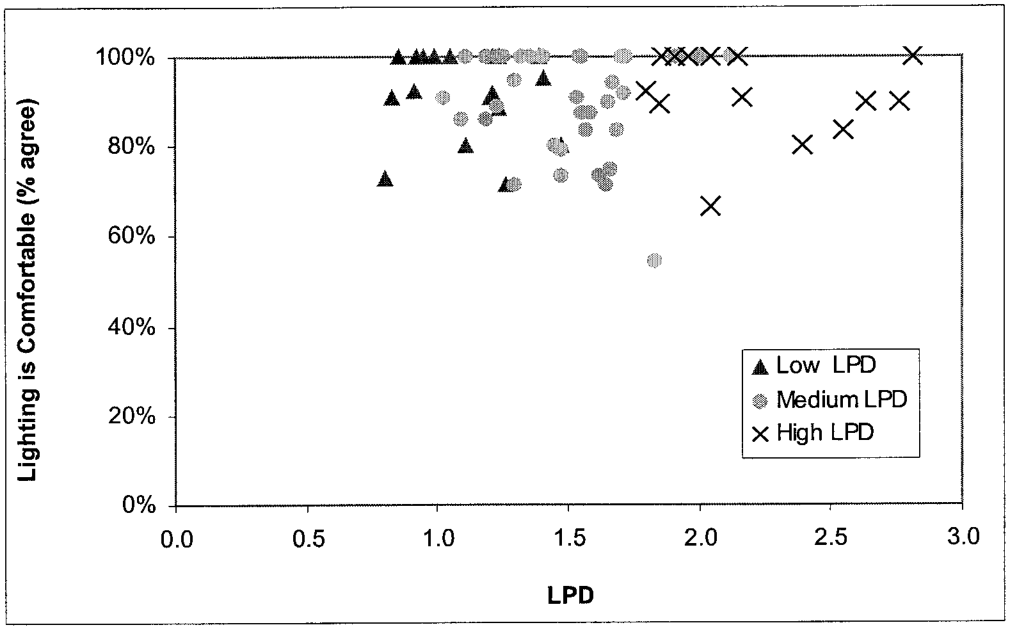

Figure 2. Overall Comfort vs. LPD

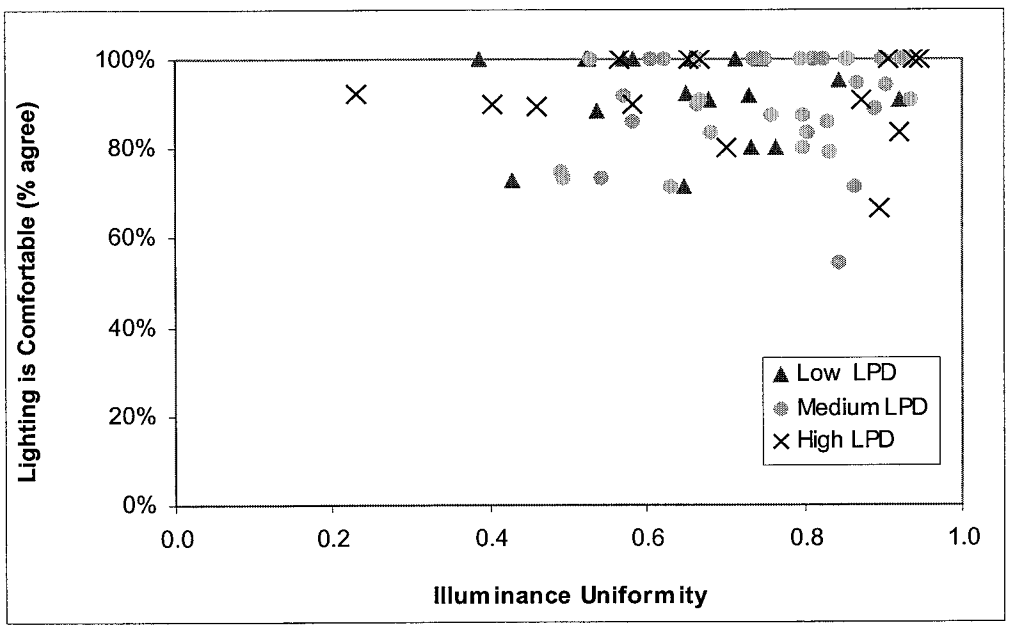

Figure 3. Overall Comfort vs. Illuminance Uniformity

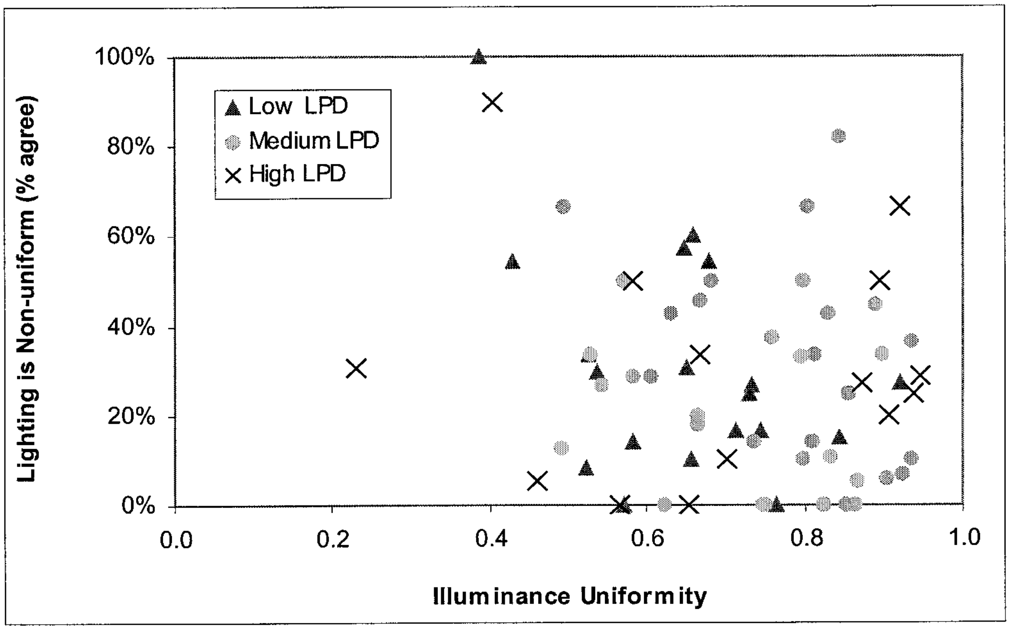

Figure 4. Occupants' Perception of Lighting Uniformity vs. Measured Illuminance Uniformity

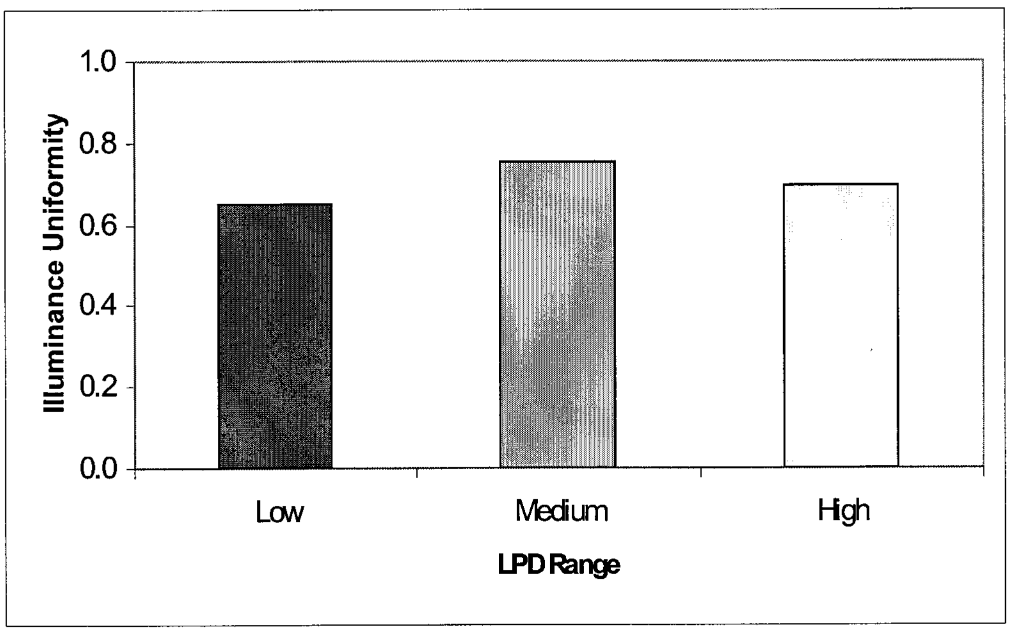

Figure 5. Measured Illuminance Uniformity by LPD Range

Conclusions

The consistency of the lighting measurement results over the three building types, the two size categories, and the three LPD categories strengthens our confidence in the Baseline Study results. In each of the categories, the lower original LPD seems to be traceable to an overcount of the measured square footage rather than an undercount of the measured lighting load. In all cases, there was no statistically significant change in the connected lighting wattage, but a consistent and usually statistically significant (though small) decrease in the measured square footage.

The lighting quality results suggest that lighting quality is not suffering as a result of reduced lighting power densities. Lighting quality is known to be a function of a variety of design considerations, such as light distribution, brightness ratios and glare conditions, but our results show that these are not systematically correlated to LPD or to horizontal illuminance. Presumably, a poor lighting quality system could be designed with a high LPD, and a good lighting quality system could be designed with a low LPD. In this study, we did not explore more deeply into the lighting quality issue, but at the simple level we did explore we found no strong evidence of lighting quality problems at any LPD level. This study, of course, addresses only a sample of newly constructed office, retail and school spaces, so these findings may not apply in other types of spaces.

However, several observations can be made from our analysis:

- Overall occupant comfort for all spaces in the sample was higher than the passing criterion, which is the norm derived from previous studies using this same occupant satisfaction survey approach.
- Although the results were consistently high, they fell into three distinct categories, referred to as "low", "medium" and "high" overall lighting comfort. With these distinctions, we were able to compare overall satisfaction responses to other indicators. At this level there was a slight correlation between overall occupant comfort and LPD and illuminance.
- Occupants' perception of lighting uniformity does not necessarily match actual illuminance uniformity based on photometric measurements. This suggests that occupant perceptions and satisfaction levels are complex responses to more factors than just footcandle levels.
- Occupants often perceived the space lighting to be non-uniform, however non-uniform lighting does not necessarily cause discomfort or dissatisfaction.

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