Lighting Quality & Measurement Error Assessment

A Follow-on to the
Nonresidential New Construction Baseline Study
Project 3

Final Report

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This report was prepared as part of the follow-on research conducted for the Non Residential New Construction (NRNC) Baseline Study, completed in 1999. This on-going work is part of a larger program of Market Assessment and Evaluation (MA&E) of energy efficiency programs aimed at the nonresidential new construction market in California. It is intended to inform policymakers and program developers who are involved in the investment of public benefits monies toward market transformation in this market segment.

The four major investor-owned energy utilities of California (Pacific Gas & Electric Company (PG&E), San Diego Gas & Electric Company (SDG&E), Southern California Edison Company (SCE), and Southern California Gas Company (SCG)) have divided among themselves the responsibilities for statewide studies of the various energy efficiency program markets. The responsibility for developing and implementing studies of the nonresidential new construction program area has been assigned to SCE. Marian Brown has overall responsibility for this MA&E area, and she has delegated management of the area to the Heschong Mahone Group (HMG), Douglas Mahone, Partner-in-Charge.

This study is one of several studies that have been designed to provide baseline and market characterization data on nonresidential new construction. The study was conducted by HMG and several contractors over a twelve month period. Catherine Chappell was the HMG Project Manager. She was supported by other HMG staff, including Lisa Heschong, Douglas Mahone, Cynthia Austin, Ihab Elzeyadi, and Jacqueline Burton.

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1. EXECUTIVE SUMMARY

The Lighting Quality and Measurement Error Assessment study consisted of two distinct elements:

- Lighting Measurement Error, and
- Lighting Quality Assessment

This 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[1]. The NRNC Baseline Study, conducted on behalf of the California Board for Energy Efficiency, estimated the energy savings relative to the 1995 Title 24[2] 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 Title 24 Standards, were attributable to lighting power savings (64% when compared to 1998 Standards)[3]. This amounted to a 9.5% reduction in total energy use (4% when compared to 1998[4]). 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 footcandles?

In order to verify the reliability of the NRNC Baseline Study survey results and to better understand the implications of reduced lighting energy use, the 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.

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[1] [1] RLW Analytics, Inc., July 1999, *California Nonresidential New Construction Baseline Study.* Sonoma, CA. Available at: www.calmac.org under 'publications'.

[2] 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.

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

[4] RLW Analytics, Inc., November 2000, *Updated Baseline – compared to 1998 Title 24 Code, Follow-on to the California Nonresidential New Construction Baseline Study.* Sonoma, CA

The first part of the study calculated the lighting power density measurement error 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 during the original Baseline Study survey.

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.

1.1 Methodology Overview

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.

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[5]. In addition, illuminance measurements were made in the surveyed spaces, using a hand-held light meter, to record light levels and uniformity. Photometric measurements were made for horizontal and vertical illuminance at a sample of locations in each space. These measurements were then used to correlate the occupants' perceptions to actual lighting conditions.

[5] [5] Eklund and Boyce, 1996, *Lighting Evaluation Toolkits,* Lighting Research Center, Rensslear Polytechnic Institute, Troy NY.

1.2 Findings

The major findings of this study are presented in two sections: Lighting Measurement Error and Lighting Quality Assessment.

1.2.1 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 what all the sources of errors are or exactly what the correct answer is. 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 1 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.

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.

The consistency of the 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.

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 1. Key Measurement Results for All Categories of Buildings

1.2.2 Lighting Quality Assessment

Our analysis shows that there is virtually no correlation between lighting quality 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.

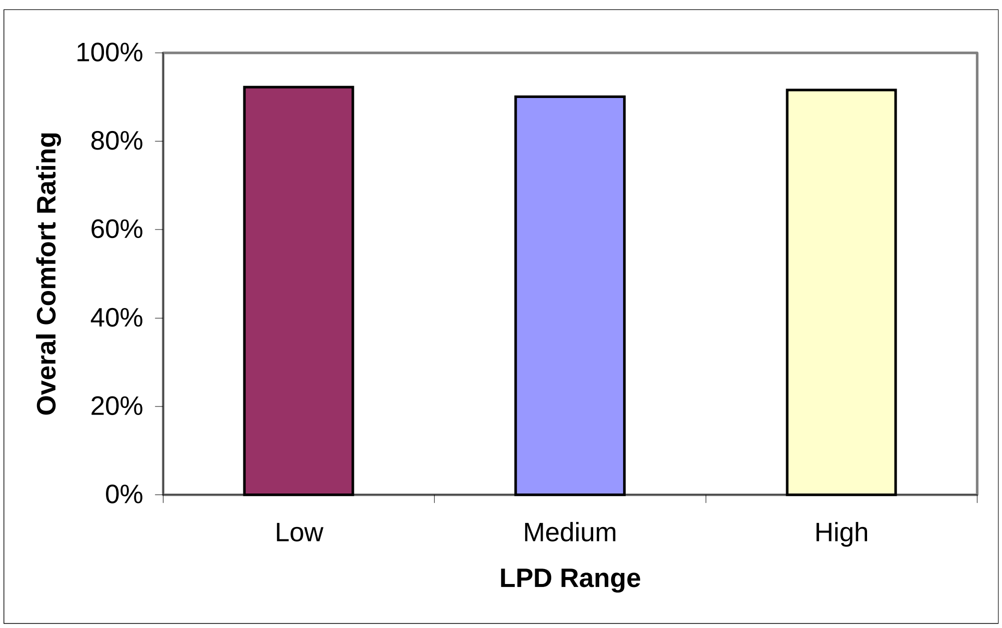

Figure 1. Overall Comfort vs. LPD Range

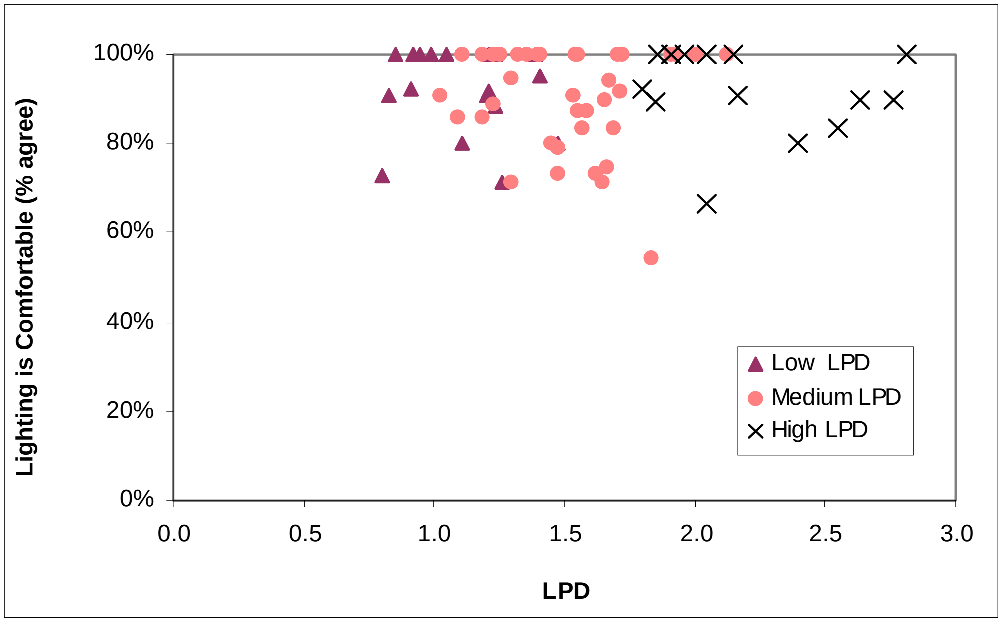

Figure 2. Overall Comfort vs. LPD

Illuminance uniformity is a quantity that describes lighting distribution. Unevenly distributed lighting can result in occupant discomfort. However, the results shown in Figure 3 indicate that this is not generally the case for the range of conditions included in this survey.

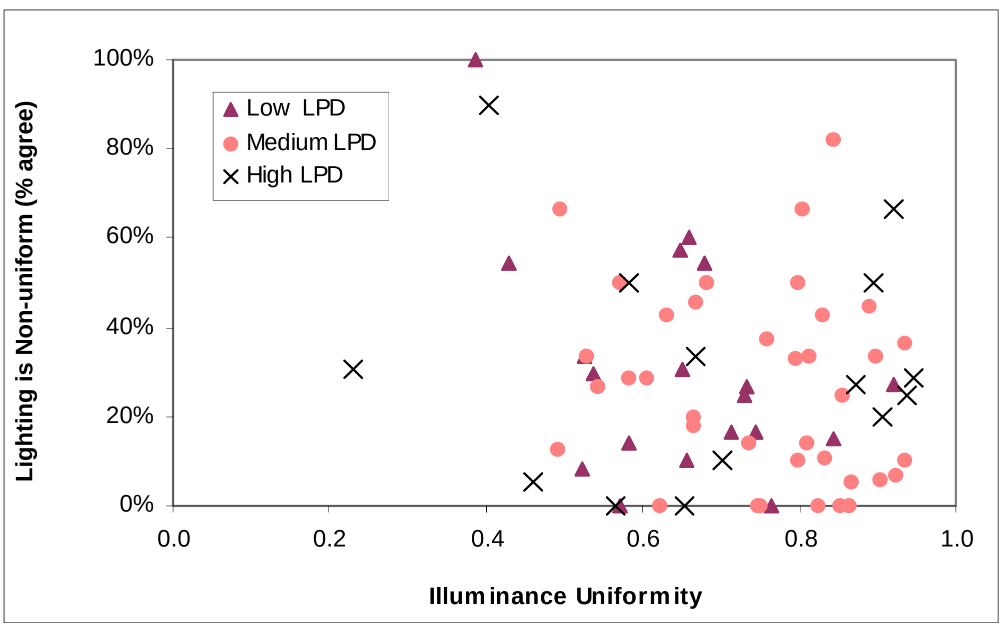

Figure 3. Occupants' Perception of Lighting Uniformity vs. Measured Illuminance Uniformity

Figure 4 shows occupants' overall comfort and satisfaction compared to measured illuminance uniformity, also showing no clear correlation between comfort and lighting uniformity in these buildings. Figure 5 presents the measured illuminance uniformity compared to LPD.

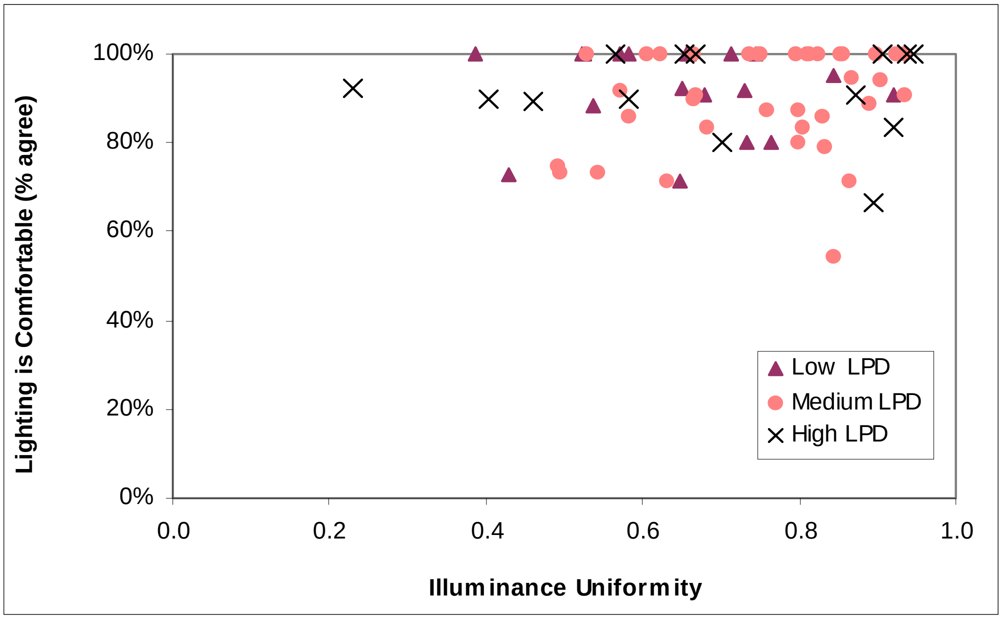

Figure 4. Overall Comfort vs. Illuminance Uniformity

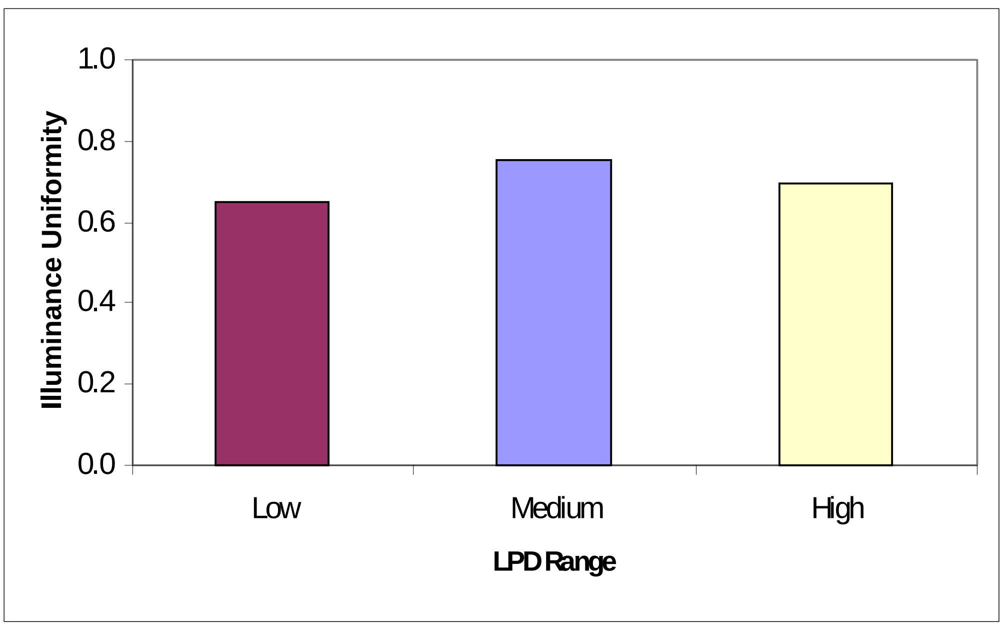

Figure 5. Measured Illuminance Uniformity by LPD Range

These results suggest that concerns about lighting quality suffering as a result of reduced lighting power densities are misplaced. Lighting quality is known to be a function of a variety of design considerations, such as light distribution, brightness ratios and color rendering, 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 deeper 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 less ordinary 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.

2. STUDY OVERVIEW

The Lighting Quality and Measurement Error Assessment study consisted of two distinct elements:

- Lighting Measurement Error, and
- Lighting Quality Assessment

This project is an extension of the work done for the Non-Residential New Construction (NRNC) Baseline Study and its database of 667 newly constructed buildings[6]. In this project we re-surveyed a sample of the sites from the Baseline Study to refine the lighting savings estimates and assess the lighting quality.

The first study objective, addressing Lighting Measurement Error, was to calculate the lighting power density measurement error 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 during the original Baseline Study survey.

The second study objective, addressing Lighting Quality Assessment, was to investigate 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.

To address both objectives, the sample needed to represent sites with low, medium, and high lighting power densities (LPD), three building types, and several building size ranges.

The sampling frame was the 562 sites in the original Baseline Study sample in three building types, office, retail and schools. These three building types account for 60% of the square footage for NRNC and 61% of the energy used by NRNC.[7] The fourth building type of the Baseline Study, public assembly, was excluded from this study because of the wide diversity of buildings in that category. A sample of 75 buildings of the 562 Baseline sites, evenly distributed across the three building types, was planned for this study. This number was chosen based on the time and budget constraints. However, both the key statistics were found to have excellent statistical precision, generally ±10% or better at the 90% level of confidence.

This study provides detailed analysis of actual conditions in key building types to better understand occupant comfort and quality related to lighting design.

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[6] RLW Analytics, Inc., July 1999, *California Nonresidential New Construction Baseline Study.* Sonoma, CA. Available at: www.calmac.org under 'publications'.

[7] "SCE/CBEE Non-Residential New Construction Baseline Scoping Study" by RLW, October 14, 1998.

2.1 Lighting Measurement Error

The issue of measurement error has been raised due to the importance of the significant lighting energy savings reported by the NRNC Baseline Study. It is reasonable to expect surveyors to make errors in their fixture counts and wattage estimates. These errors could be systematic or random. If, for example, the surveyors tended to under-count the number of fixtures, then the resulting energy savings estimates could be systematically biased as too large. If, however, the errors were random, then they would tend to cancel each other and the savings estimates would be more reliable. We have quantified these numbers to determine the sign and magnitude of any measurement error in the lighting power density numbers presented in the NRNC Baseline Study. Further, we have examined the sources and types of measurement errors that seem to have occurred.

2.2 Lighting Quality Assessment

The correlation between lighting power densities and lighting quality has also been raised as an issue due to the importance of lighting energy savings reported by the NRNC Baseline Study. Some lighting designers have asserted that unskilled lighting practitioners would be unable to produce acceptable lighting quality in projects designed with low levels of lighting power. If this were true, then a significant portion of buildings in the Baseline sample would have low lighting quality, since many of them had low LPDs.

Many different definitions of lighting quality have been proposed; some based on photometric measurements and others based on behavioral outcomes. In this study we present our results by comparing lighting power densities and illuminance measurements to behavioral outcomes. Using this approach we hope to identify any lighting quality deficiencies associated with low lighting levels.

The premise for 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, occupants' attitudes toward lighting quality were collected using a simple, nationally normalized, lighting quality assessment questionnaire. Illuminance measurements were made in the surveyed spaces to correlate the occupants’ perceptions to actual lighting conditions. Additionally, descriptions of the lighting system design characteristics were collected in order to develop an explanatory understanding of the quantitative findings.

2.3 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.

3. STUDY METHODOLOGY

This section explains in greater detail the methodology that was used to conduct this study.

Detailed protocols were developed for all phases of the study including; recruiting and scheduling, detailed lighting inventory, and lighting quality assessment. The on-site data collection consisted of two distinct tasks: light fixture counts and lighting quality assessment.

The study followed these basic steps:

1. Draw a sample from the California NRNC Baseline Study sites. The sample was grouped by lighting power density (LPD) in W/sf and building size for each of the three building types (office, retail, schools).
2. Develop protocols for recruitment and data collection.
3. Recruit the sampled buildings to cooperate with the study.
4. Collect detailed on-site lighting data for each building such as physical dimensions and lighting fixture types and quantities.
5. Administer the lighting quality assessment survey to the occupants in the spaces.
6. Sketch the site plan and record details of the measurement area.
7. Take illuminance measurements in representative locations.
8. Take photographs of the measurement area.
9. Enter data into a database.
10. Estimate the measurement error.
11. Analyze the lighting quality.

The research design insured that during the initial contact, the on-site visit, and the data review, careful attention was paid to verifying that the surveyed site had indeed not changed since the original survey. If the discrepancies were significant the site was abandoned because we did not want the measurement error determination to be confused with persistence problems or changes in lighting system characteristics.

3.1 Sample Selection

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.

3.1.1 Original Population and Sample

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 2 shows the number of sites in each category from the original NRNC Baseline sample.

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

Table 2. Number of Available Sites by Building Type

The first step in developing the sample design was to eliminate sites that would be potential problems in the field. Sites were only retained if a high proportion of the space was in the primary space type – office space for offices, retail space for retail buildings, and classroom space for schools. We did this in order to avoid sites such as school-bus garages that might have been classified as schools. We also restricted the population to new buildings, thereby dropping renovations and additions, in order to minimize the chance of error in identifying the space that was originally audited and modeled. We also excluded nineteen large sites greater than 100,000 square feet. A detailed analysis of the sample frame showed that the LPD and energy ratio of the sites, by building type, did not vary by building size. Therefore, we reasoned, the results from the large site would be similar to the results from the smaller sites. Due to time and budget constraints we did not want to include buildings that would require more than one day of fieldwork. Finally, we excluded one office site in the 50,000 – 100,000 SF size category, with LPD greater than 1.75 W/sf since there was only one site in this size/LPD segment.

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 3 shows the cut-points selected for defining these three LPD levels. For example, in the office category, a site was considered to have low LPD if its LPD was less than 1.0 Watt per square foot, and high if its LPD was greater than 1.75 Watt per square foot. Note that these are whole building LPDs, not the LPDs for individual spaces. Data collected during the original survey was aggregated up to the whole building level to determine the building level LPD.

LPD		
Low	**Medium**	**High**
<1.0	1.0 - 1.75	>1.75
<1.5	1.5 - 2.5	>2.5
<1.0	1.0 - 1.75	>1.75

Table 3. LPD Categories

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 was stratified by building size and lighting power density (LPD). Seventy-five sites were selected following the stratified sampling plan shown in Table 4. A complete description of the sampling procedure is provided in Appendix G.

Type	Size (kSF)	LPD (W/SF)	Population	Sample
Office	0 - 50	0 - 1	19	7
Office	0 - 50	1 - 1.75	50	7
Office	0 - 50	> 1.75	9	7
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	7
Retail	0 - 50	> 2.5	13	7
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	7
School	0 - 50	1 - 1.75	47	7
School	0 - 50	> 1.75	12	7
School	50 - 100	0 - 1	2	1
School	50 - 100	1 - 1.75	14	1
Total			317	75

Table 4. Population and Sample

3.1.2 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:

1) Change to the lighting system,
2) Change in occupancy,
3) Change in space configuration or size.

Once the sites were selected and screened an on-site data collection visit was scheduled. The screening and scheduling instrument is provided in Appendix A.

3.1.3 Final Population and Sample

The target sample for this project was 75 office, retail and school sites from the original Baseline Study. 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 5 presents the final sample by building type for each component of the study.

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

Table 5. Final Sample

3.2 Lighting Measurement Error

The lighting measurement task carefully re-surveyed a sample of Baseline Study sites to get a better understanding of installed lighting power by building type, and 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 measurements 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. A sample of the Re-survey Form is provided in Appendix B.

Surveyors were usually able to identify any gross discrepancies between the building they were in and the data on the re-survey form with the level of information provided. When the surveyors observed that there had been an apparent change since the original survey, they questioned the site contact further to confirm. Although every attempt was made during the screening process and while on-site to determine if the lighting system had changed since the original survey, the study objectives and re-survey procedures made it impossible to catch all cases. Ultimately ten sites were dropped from the analysis due to this issue. Some of the sites were initially surveyed in 1996 so the recollection of the site contact may not be 100% dependable. For example, the site contact at one site was sure that no retrofit had been made to the space. However, follow-up with staff who had been there longer than he had suggested there had been a change. While conducting the on-site survey, it is important to gain the trust and assistance of the site contact, therefore the surveyors were not in a position to question the site contact in depth.

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.

3.3 Lighting Quality Assessment

Lighting quality was assessed by correlating lighting power densities and illuminance measurements to occupants' attitudes towards lighting comfort. Occupants' attitudes were collected using a simple questionnaire, which asked a series of yes/no questions regarding the lighting in the space.

The lighting quality measurements and the criteria to which they were compared are shown in Table 6. 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.

Quantity	***Measurement Method***	***Criterion to pass (source)***
% finding the lighting comfortable	*lighting survey questionnaire*	*>70% (normative data)*
average illuminance	*illuminance measured at sample points*	*variable according to situation (IESNA Handbook, 1993)*
illuminance uniformity	*min./avg. illuminance measured at sample points*	*>0.8 (CIBSE Code for Interior Lighting, 1994)*
LPD (W/sf)	*calculation from total lighting fixture count and floor area measurement*	*variable according to situation (ASHRAE/IES 90.1 1989)*

Table 6. Lighting Quality Measurements and Criteria for Passing

3.3.1 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.

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 in the following sub-sections.

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.

Office Lighting Measurements

Illuminance measurements were made at representative, but usually vacant, work stations or desks in each office, so as to minimize disruption to the occupants. On each desk, the illuminance measurements were made at six locations on the desk surface. Vertical measurements were taken on the plane of the computer screen.

Vertical measurements were made on the upper walls approximately two feet below the ceiling with the light meter held flat against the wall. This measurement was made to gauge the general ambient illuminance of the space.

Retail Lighting Measurements

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.

Classroom Lighting Measurements

The surveyors selected a typical, but usually vacant, classroom 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.

3.3.2 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[8]. 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 surveyors collected all questionnaires after they had completed their data collection tasks, allowing sufficient time for the occupants to complete the questionnaire.

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

[8] Eklund and Boyce, 1996, *Lighting Evaluation Toolkits,* Lighting Research Center, Rensslear Polytechnic Institute, Troy NY.

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.

The lighting quality questionnaires are provided in Appendix B.

4. LIGHTING MEASUREMENT ERROR RESULTS

The first objective of this study was to was to calculate the lighting power density (LPD) measurement error, and 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 during the original Baseline Study survey. This chapter presents the analysis and results from the Measurement Error task.

Re-survey lighting measurement results were compared to the existing survey data from the NRNC Baseline Study. For each site in the sample, new and original wattage and square footage measurements were compared as a ratio of the new measurement to the original measurement. A ratio of the LPDs derived from the new and original measurements was also calculated. The results were then projected back to the population.

For any measurement that had more than a 20% difference in wattage, square footage, or LPD, a detailed investigation of the data was conducted to identify and describe the reason for the discrepancies.

Based on the final sixty-five sites in the sample, case weights were calculated to project the sample results back to the target population.

Table 7 shows how the weights have been calculated for the analysis based on the 65 sites. In each stratum, the case weight is simply the size of the population divided by the size of the sample. All of the results reflect these weights.

Type	Size (kSF)	LPD (W/SF)	Population	Sample	Weight
Office	0 - 50	0 - 1	19	3	6.33
Office	0 - 50	1 - 1.75	50	10	5.00
Office	0 - 50	> 1.75	9	4	2.25
Office	50 - 100	0 - 1	10	2	5.00
Office	50 - 100	1 - 1.75	27	2	13.50
Retail	0 - 50	0 - 1.5	15	7	2.14
Retail	0 - 50	1.5 - 2.5	46	8	5.75
Retail	0 - 50	> 2.5	13	4	3.25
Retail	50 - 100	0 - 1.5	18	2	9.00
Retail	50 - 100	1.5 - 2.5	18	2	9.00
Retail	50 - 100	> 2.5	9	2	4.50
School	0 - 50	0 - 1	8	1	8.00
School	0 - 50	1 - 1.75	47	10	4.70
School	0 - 50	> 1.75	12	5	2.40
School	50 - 100	0 - 1	2	1	2.00
School	50 - 100	1 - 1.75	14	2	7.00
Total			317	65	

Table 7. Population, Sample, and Weights

4.1 Population Level Analysis

Table 8 shows the overall measurement error results for all building types that reflect the target population. The average floor area of the original surveyed space was 42,512 square feet per building. The average re-surveyed area was 40,352 square feet per building or 5% less than the original measurement. This difference would tend to make the original surveyed lighting power density numbers smaller than the re-surveyed results (the original denominator was smaller than the re-surveyed denominator).

In a study such as this, there is always some chance that the space that was re-surveyed was different than the space studied in the original survey. However, we have tried to minimize this type of mistake. As explained previously, renovations and additions were excluded from the target population in order to minimize the chance that the space might not be correctly identified. In a few instances, the surveyor visited a different site than the original building that was surveyed. These sites were dropped from the sample and are not reflected in these results. So most of the difference in square footage is believed to represent measurement error. Nevertheless, we cannot completely exclude the possibility of differences between the two spaces that were surveyed.

Table 8 also shows the average total connected wattage of the lighting in the original space, 57,884 Watts per building. The average total connected lighting wattage of the re-surveyed space was 57,264 Watts per building, 1.1% lower than the original measurement. This difference would tend to make the original LPDs larger than the re-surveyed (the original numerator was slightly larger than the re-surveyed numerator). Again the difference is believed to be measurement error, because extensive efforts were made to assure re-surveys of unchanged spaces, but we cannot exclude the possibility of changes in the facility or differences in the space that was surveyed.

All Buildings	Original	Resurvey
Square Footage	42,512	40,353
Total Watts	57,884	57,264

Table 8. Average Square Footage and Watts for the Population

Table 9 shows the measurement results by building type. The original square footage measurements are consistently larger than the re-surveyed measurements. The original wattages for office and retail are greater than the re-survey, while the original school wattage was less.

Bldg. Type	Square Footage		Total Watts		Sample Size
	Original	Resurvey	Original	Resurvey	
Office	27,975	26,098	27,679	26,675	21
Retail	58,058	55,076	92,813	90,527	25
School	40,367	38,994	49,654	51,954	19

Table 9. Average Square Footage and Watts by Building Type

Table 10 shows key ratios for wattage, area and lighting power density (Watts per square foot) derived from the results. The ratio between the re-surveyed connected lighting wattage and the original connected lighting wattage is 0.989. In other words, the re-survey indicates that the original wattage was slightly over-counted by 1.1%. The error bound on this statistic was calculated to be ±0.042. The 90% confidence interval is the estimate plus or minus the error bound, (0.947, 1.031). The relative precision[9] of the estimate was found to be ±4.2% at the 90% confidence level. Since the confidence interval includes the value of one, the observed ratio is not statistically different than one. The difference between the original and re-surveyed connected lighting wattage is not statistically significant. Some small error was observed, but this is probably unavoidable in building field survey research.

The ratio between the re-surveyed area and the original area is 0.949. These results suggest that the square footage might have been over-counted originally by 5.1%. More rigorously speaking, either the square footage was over-counted in the original survey or there is some difference in the space surveyed the two

9 Relative precision reflects the variation expected in a sample statistic such as a ratio from one sample to another sample throughout the 'population' of all possible samples. Relative precision can also be described with the following example: If a confidence interval is A +/- B then the relative precision, is B/A. Here A can be called the estimate and B the error bound.

times. The error bound was calculated to be ±0.030. The 90% confidence interval, (0.919, 1.031), suggests that, although the difference is relatively small, it is less than one and therefore significant at the 90% confidence level.

Table 10 also shows the original and re-surveyed lighting power density (Watts per square foot). The results show that the lighting power density (LPD) was originally estimated to be 1.36 Watts per square foot, and in the re-survey it was found to be slightly higher at 1.42 Watts per square foot. The difference is 0.058 Watts per square foot, or 4%. The confidence interval for the difference is (-0.014, 0.129) so the difference in the LPD is not significantly different from zero at the 90% level of confidence.

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	

Table 10. Key Ratios & Measurements, All Building Types

The following sections provide additional analysis of the results.

4.1.1 Results by Building Type

This section provides the results by building type.

Offices

The ratios in Table 11 for the offices are similar to the results for all building types shown in Table 10. The lighting intensity was originally estimated to be 0.99 Watts per square foot, and in the re-survey it was found to be slightly higher, 1.02 Watts per square foot. The difference is 0.033 Watts per square foot, or 3%. The confidence interval for the difference is (-0.082, 0.148) so the difference is not significantly different from zero at the 90% level of confidence. As with the overall results, the original survey may have slightly undercounted the installed LPD, and therefore slightly over-estimated the savings.

Ratios & Measurements	Estimate	Err Bnd	Low	High	Rel Prec
Resurv. Watts vs. Orig. Watts	0.964	0.080	0.884	1.044	0.083
Resurv. Area vs. Orig. Area	0.933	0.041	0.892	0.974	0.044
Orig. LPD	0.989	0.133	0.856	1.122	0.134
Resurv. LPD	1.022	0.052	0.971	1.074	0.050
Resurv. LPD - Orig. LPD	0.033	0.115	-0.082	0.148	

Table 11. Key Ratios & Measurements, Offices

Retail

The ratios in Table 12 for retail are similar to the results for all building types shown in Table 10. The lighting intensity was originally estimated to be 1.60 Watts per square foot, and in the re-survey it was found to be slightly higher, 1.64 Watts per square foot, or 3%. The difference is 0.045 Watts per square foot. The confidence interval for the difference is (-0.75, 0.165) so the difference is not significantly different from zero at the 90% level of confidence. As with the overall results, the original survey may have slightly undercounted the installed LPD, and therefore slightly over-estimated the savings.

Ratios & Measurements	Estimate	Err Bnd	Low	High	Rel Prec
Resurv. Watts vs. Orig. Watts	0.975	0.061	0.915	1.036	0.062
Resurv. Area vs. Orig. Area	0.949	0.051	0.897	1.000	0.054
Orig. LPD	1.599	0.093	1.506	1.692	0.058
Resurv. LPD	1.644	0.118	1.525	1.762	0.072
Resurv. LPD - Orig. LPD	0.045	0.120	-0.075	0.165	

Table 12. Key Ratios & Measurements, Retail

Schools

The ratios in Table 13 for the schools are similar to the results for all building types shown in Table 10. The lighting intensity was originally estimated to be 1.23 Watts per square foot, and in the re-survey it was found to be slightly higher, 1.33 Watts per square foot. The difference is 0.102 Watts per square foot, or 8%. The confidence interval for the difference is (0.002, 0.203) so although the difference is relatively small, it is just barely statistically significant at the 90% level of confidence. The original survey may have slightly undercounted the installed LPD, and therefore slightly over-estimated the savings.

Ratios & Measurements	Estimate	Err Bnd	Low	High	Rel Prec
Resurv. Watts vs. Orig. Watts	1.046	0.054	0.993	1.100	0.051
Resurv. Area vs. Orig. Area	0.966	0.043	0.923	1.009	0.044
Orig. LPD	1.230	0.124	1.106	1.354	0.101
Resurv. LPD	1.332	0.099	1.233	1.431	0.074
Resurv. LPD - Orig. LPD	0.102	0.100	0.002	0.203	

Table 13. Key Ratios & Measurements, Schools

In summary, the results observed for the three building types were essentially the same as observed for all buildings taken together. The difference in wattage was not statistically significant for any of the three building types. In each of the three building types, the re-surveyed square footage was consistently slightly smaller than the original square footage. Most important, the re-surveyed LPD was consistently slightly higher than the original survey. The increase was greatest for the schools, but even in this case it was only 0.1 Watts per square foot. The wattage and square footage measurements and resulting LPD were not significantly different at the 90 percent confidence interval.

4.1.2 Results by Size

The analysis was carried out for the two size categories: small buildings (0 – 50 ksf), and medium buildings (50 ksf– 100 ksf). Table 14 shows the square footage and wattage measurements by building size. The results are consistent with the overall results and results by building type.

Bldg. Size	Square Footage		Total Watts		Sample Size
	Original	Resurvey	Original	Resurvey	
0k - 50k	24,035	23,345	33,333	33,876	52
50k - 100k	83,804	78,361	112,746	109,527	13

Table 14. Average Square Footage and Watts by Building Size

Table 15 shows the key ratios calculated for small buildings. As with the other results, the difference in the Watts per building is not statistically significant. The difference in the square footage is small but statistically significant, with the original square footage slightly larger than the re-surveyed square footage.. The LPD was found to be slightly higher in the re-survey, but the difference was only 0.064 Watts per square foot, or 4.6%.

Ratios & Measurements	Estimate	Err Bnd	Low	High	Rel Prec
Resurv. Watts vs. Orig. Watts	1.016	0.028	0.989	1.044	0.027
Resurv. Area vs. Orig. Area	0.971	0.026	0.945	0.998	0.027
Orig. LPD	1.387	0.103	1.284	1.490	0.074
Resurv. LPD	1.451	0.097	1.354	1.548	0.067
Resurv. LPD - Orig. LPD	0.064	0.051	0.013	0.115	

Table 15. Key Ratios & Measurements, Small Buildings

Table 16 shows the same key ratios for the medium-sized buildings. As with other results, the difference in the Watts per building is not statistically significant. The difference in the square footage is small but statistically significant, with the original square footage slightly larger than the re-surveyed square footage. The original LPD was slightly lower than the re-survey LPD, but the difference was only 0.052 Watts per square foot, or 3.9%, and was not statistically significant.

Ratios & Measurements	Estimate	Err Bnd	Low	High	Rel Prec
Resurv. Watts vs. Orig. Watts	0.971	0.067	0.905	1.038	0.069
Resurv. Area vs. Orig. Area	0.935	0.047	0.888	0.982	0.051
Orig. LPD	1.345	0.158	1.187	1.504	0.118
Resurv. LPD	1.398	0.143	1.255	1.541	0.102
Resurv. LPD - Orig. LPD	0.052	0.112	-0.060	0.165	

Table 16. Key Ratios & Measurements, Medium Buildings

In summary, the results observed by building size were essentially the same as observed for all buildings taken together.

4.1.3 Results by Original Lighting Power Density Category

The analysis was also carried out for the three LPD categories: low, medium, and high. Table 17 shows the definition of each category, which were used in the sampling plan.

Type	Original LPD (W/sf)	Category
Office	0 - 1	Low
Office	1 - 1.75	Medium
Office	> 1.75	High
Retail	0 - 1.5	Low
Retail	1.5 - 2.5	Medium
Retail	> 2.5	High
School	0 - 1	Low
School	1 - 1.75	Medium
School	> 1.75	High

Table 17. Definition of LPD Categories

Table 18 shows the measurement summary by LPD category.

LPD Range	Square Footage		Total Watts		Sample Size
	Original	Resurvey	Original	Resurvey	
Low	51,653	45,500	63,205	63,891	16
Medium	41,248	40,553	54,615	54,006	34
High	33,148	30,797	64,331	61,467	15

Table 18. Average Square Footage and Watts by LPD Category

Table 19 shows the key ratios calculated for low LPD buildings. As before, the difference in the Watts per building is not statistically significant. The difference in the square footage is small but statistically significant, with the square footage slightly larger in the original measurement. The original re-surveyed LPD was lower than the re-survey by 0.2 Watts per square foot. An explanation for this relatively large difference (compared to the other results) is provided at the end of this section.

Ratios & Measurements	Estimate	Err Bnd	Low	High	Rel Prec
Resurv. Watts vs. Orig. Watts	1.011	0.114	0.897	1.125	0.113
Resurv. Area vs. Orig. Area	0.881	0.023	0.858	0.904	0.027
Orig. LPD	1.224	0.127	1.097	1.350	0.104
Resurv. LPD	1.404	0.219	1.185	1.623	0.156
Resurv. LPD - Orig. LPD	0.181	0.148	0.032	0.329	

Table 19. Key Ratios & Measurements, Low LPD

Table 20 shows the key ratios calculated for the buildings in the medium LPD category. The difference in the Watts per building and the square footage are both not statistically significant. However, as usual, the square footage was slightly larger in the original. The original LPD was slightly lower than the re-surveyed LPD, but the difference was less than 0.01 Watts per square foot.

Ratios & Measurements	Estimate	Err Bnd	Low	High	Rel Prec
Resurv. Watts vs. Orig. Watts	0.989	0.047	0.942	1.036	0.048
Resurv. Area vs. Orig. Area	0.983	0.033	0.950	1.016	0.034
Orig. LPD	1.324	0.154	1.170	1.478	0.116
Resurv. LPD	1.332	0.107	1.225	1.438	0.080
Resurv. LPD - Orig. LPD	0.008	0.080	-0.073	0.088	

Table 20. Key Ratios & Measurements, Medium LPD

Table 21 shows the key ratios calculated for the buildings in the high LPD category. The results are similar to those found for the medium LPD category. The difference in the Watts per building and the square footage are both not statistically significant. However, as usual, the square footage was slightly larger in the original survey. The original LPD was slightly lower, but the difference was less than 0.06 Watts per square foot.

Ratios & Measurements	Estimate	Err Bnd	Low	High	Rel Prec
Resurv. Watts vs. Orig. Watts	0.955	0.074	0.882	1.029	0.077
Resurv. Area vs. Orig. Area	0.929	0.113	0.816	1.042	0.122
Orig. LPD	1.941	0.154	1.786	2.095	0.080
Resurv. LPD	1.996	0.217	1.779	2.213	0.109
Resurv. LPD - Orig. LPD	0.055	0.116	-0.061	0.171	

Table 21. Key Ratios & Measurements, High LPD

In summary, the results by original LPD category were substantially the same as the overall results. There is a larger LPD increase in the low LPD category than in the medium and high LPD categories. However, this might be expected from a statistical artifact called the regression to the mean. The following is a non-technical explanation of this well-known phenomenon.

Suppose that there is some statistically independent, random measurement error in the LPD measurements in both the original and new surveys. In other words, assume that the measured LPD is an unbiased estimate of the true LPD of each site, but subject to an error that might be positive or negative purely at random. Then when the sample sites are categorize into the three LPD categories, the sites in the low LPD category will tend to have negative measurement error in the initial survey whereas the sites in the high LPD category will tend to have positive measurement error in the initial survey. Under our assumption that the measurement error in the second survey is independent of the measurement error in the first survey, there will be some tendency for the LPD to increase in the low LPD category, simply because the initial measurement error tended to be negative due to the categorization. Conversely, there will be some tendency for the LPD to decrease in the high LPD category, simply because the initial measurement error tended to be positive due to the categorization. Therefore, we would expect to see a larger increase in the LPD in the low category relative to the high category, simply due to the categorization.

The more important point is that, even in the low LPD category, the measurement error appears to be small, less than 0.2 Watts per square foot. So it seems evident that we can conclude that measurement error is not a material issue in interpreting the results of the Baseline Study. In other words, we believe this follow-up study has shown that the original lighting measurements were substantially accurate.

4.2 Measurement Error Findings

The general conclusion from the results is 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 what all the sources of errors are or exactly what the correct answer is. Rather, we rely on the statistical margins of error to re-assure us that the survey data is accurate for all practical purposes. Users must be aware of the limits to accuracy in using the 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. The overall average measurement results for the population are presented in Table 22.

All Buildings	Original	Resurvey
Total Watts	57,884	57,264
Square Footage	42,512	40,353
LPD (W/sf)	1.36	1.42

Table 22. Population Level Measurement Results

Our calculations indicate that the lighting intensity 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. So we believe the observation we have found are characteristic of the 317 buildings in the original sample frame from the NRNC Baseline Study.

The consistency of the 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 *increase* in the measured square footage rather than a decrease in 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 decrease in the measured square footage.

Of course, it seems unlikely that there could be an actual decrease in the square footage in all of our different categories of analysis between the first and the second survey. Was there a change in the emphasis given to the importance of square footage? The later seems likely. In the initial surveys, the surveyors knew the fundamental purpose was to measure and model the energy efficiency of the building. By contrast, in the second study, there was a much stronger focus on LPD. And square footage is obviously a central factor in the LPD. So perhaps, the surveyors took more care about their square footage measurements the second time around. This still leaves unexplained why square footage tended to be measured systematically *lower* in the second study than the initial study. This fact would suggest a systematic change in the procedures used to measure square footage in the two studies. While no specific evidence is available, it is a plausible explanation for the consistent discrepancies.

4.2.1 Comparison of All Sites

This section discusses the analysis and results of the 65 sites in the sample. Once the wattage and square footage data from the re-survey were entered in the database, analysis consisted of comparing original and re-survey measurements and resulting LPDs. Table 23 summarizes the results by building type for the sites in the sample. The graphs presented in this section show the comparison of kW, square footage, and LPD for the sample of re-surveyed sites, in terms of ratios. The ratio is calculated as the re-surveyed results over the original results. A value less than 1.00 means that the original measurement was larger than the re-surveyed measurement. A value greater than 1.00 means that the original measurement was smaller than the re-surveyed measurement.

Bldg. Type	kW	Bldg. Area (sf)	LPD
Office	0.96	0.98	0.99
Retail	1.02	0.95	1.08
School	1.03	0.97	1.08
Total	1.00	0.97	1.05

Table 23. Summary of kW, Area and LPD Ratios

Figure 6 presents the overall LPD comparison for all of the sites. The graph shows that a positive correlation exists between the original and re-surveyed LPD with a few outliers. The results for square footage and wattage show a similar positive correlation and are presented in Appendix D.

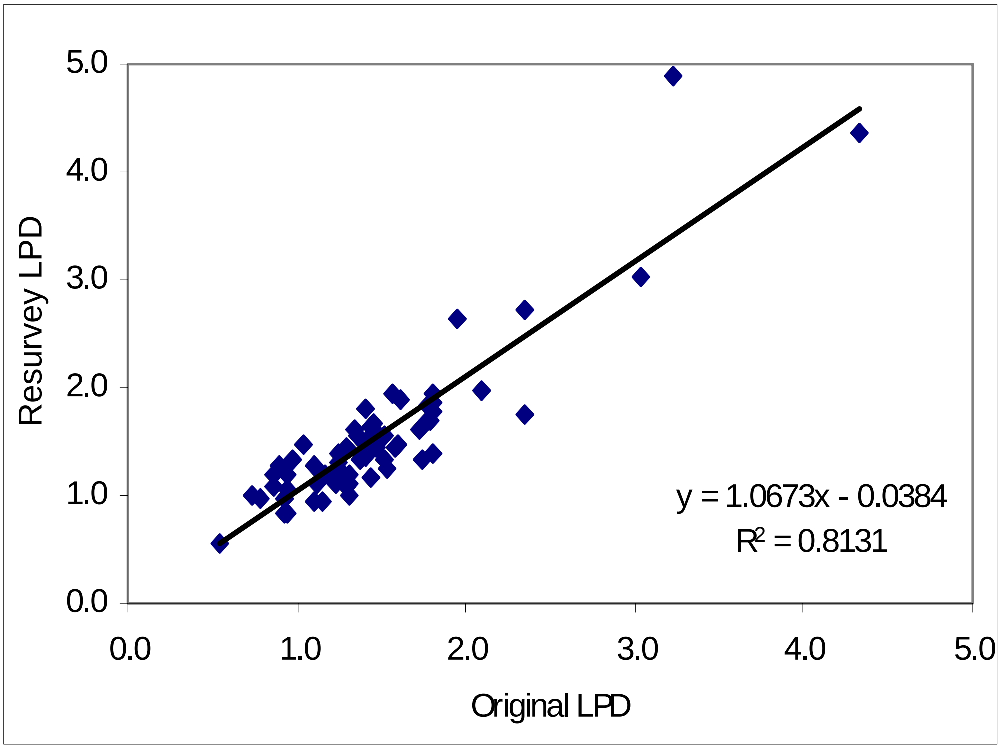

Figure 6. Overall LPD Comparison

4.2.2 Reasons for Discrepancies

For any measurement that had more than a 20% difference in wattage, square footage, or LPD, a detailed investigation of the data was conducted to identify and describe the reason for the discrepancies. There are ten error types that describe the discrepancies. The sources of discrepancies shown in Table 24 are sorted by type.

The first four are identified simply as “discrepancies between measurements” because the “correctness” of one measurement over the other could not be determined. Error number 4 is an aggregate of the first three that results in an LPD difference of more than 20%. The three original survey errors (codes 5 – 7) were identified as specific errors in the original survey data. Errors 6 and 7 were secondary errors and did not result in significant differences in the two measurements.

Note that the first seven errors were assigned numerical codes and the last three were assigned alphabetical codes. These last three were summarized as re-survey errors. Sites with these types of errors were dropped from the final comparison since the objective was to look for sources of errors in the original data, not to introduce new sources of error.

One measurement error type was assigned to each site that had an LPD error greater than 20%. Sites with multiple errors were assigned the most significant error in terms of impact on LPD.

Code	Description	Type
0	no significant differences (+/- 20% LPD)	
1	fixture count	discrepancies between measurements
2	fixture type	discrepancies between measurements
3	measured area	discrepancies between measurements
4	aggregated errors (sf & W)	discrepancies between measurements
5	miscalculated/measured areas	Original survey error
6	space sampling error	Original survey error
7	data entry errrors	Original survey error
a	area mismatches	Re-survey survey error
b	building mismatches	Re-survey survey error
c	mis/un-reported retrofits	Re-survey survey error

Table 24. Measurement Error Classifications

As shown in Table 25, the most common errors in terms of percent difference in LPD were:

- fixture type difference (error code 2)
- miscalculated areas (error code 5)
- area measurement error (error code 3)

Fixture count difference (error code 1) has a relatively low average percent difference and few occurrences, however the magnitude of the site-specific differences range from 23% to –45%. This suggests that the original surveyors were just as likely to over-count as to under-count the fixtures, without creating any bias.

Code	Description	Occurences	Dif.
0	no significant differences (+/- 20% LPD)	48	0.3%
1	fixture count	4	-3.6%
2	fixture type	3	-39.7%
3	measured area	2	-23.9%
4	aggregated errors (sf & W)	7	-16.2%
5	miscalculated/measured areas	1	-34.9%

Table 25. Measurement Error Magnitudes

As described previously, ten sites were dropped from this analysis due to “building mis-matches” in the re-survey (error codes a through c). While this may sound like a fairly simple issue to have resolved, it is understandable that some of the sites “slipped through the cracks” during the recruiting and screening process. Some of the sites were initially surveyed in 1996 so the recollection of the site contact during our recruitment and re-survey process may not have been 100% dependable. In other cases we learned that many building occupants or operators did not fully understand what we meant by a lighting system change. This is evidenced in the following description of a site contact response when re-contacted and asked “Are you sure there have not been any changes to your building?” based on significant discrepancies between the original and new survey data. The last statement suggests that the person we spoke with did not consider a change in lamp wattage to be a system change.

> *The construction department contact for this chain store indicated that they have not done any lighting changes on purpose since the store was first built. He continued that when maintenance is done for replacement, different lamps may have been installed, but it would have been done by the contractor, so his department would not be aware of the change. He then added that as of this year, they no longer use 400W lamps, but rather 175W lamps.*

4.2.3 Comparison across All Categories

Table 26 summarizes the key measurement results for the population. The first row shows the results for all buildings taken together. In every category, the average area per building in the original survey was larger than the average area per building in the re-survey. The average Watts of connected lighting also tended to be slightly larger.

In each case, the average LPD was found to be slightly lower in the original survey than the re-survey. In the preceding discussion we saw that the difference in average LPD was generally not statistically significant. However, the consistency of the results across all of these categories supports a tentative conclusion that the original survey may have slightly underestimated the LPD. But the difference appears to be very small, no more than 5% overall. The difference seems to be associated with the difference in square footage more than the difference in connected lighting.

Further statistical details of these results are presented in Appendix E.

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 26. Key Results and Ratios for All Categories of Buildings

5. LIGHTING QUALITY ASSESSMENT RESULTS

The second objective of this study was to research the correlation between lighting power density (LPD) and lighting quality. The results from the lighting quality assessment measurements were summarized by correlating the lighting quality responses to space LPD and illuminance measurements. The comparison was done for each of the three building types. This chapter presents the analysis and results from the Lighting Quality Assessment task.

5.1 Quality Assessment Analysis

The lighting quality survey results were used to derive four measures of lighting quality:

- The percentage of respondents with a positive overall opinion of the lighting.
- The percentage of respondents finding the lighting uncomfortably dim.
- The percentage of respondents finding the lighting uncomfortably bright.
- The percentage of respondents considering the lighting non-uniform.

These responses were investigated, by space type, to determine if there is a correlation between occupant satisfaction and lighting intensities (LPD) and illuminance levels. The average satisfaction value was calculated for each of the spaces and correlated to LPD and average illuminance measurements.

The questions and the normative criteria against which they were compared are shown in Table 27. High percentages for the first two questions indicate high satisfaction. Low percentages for the third through the eleventh question indicate high satisfaction. The same office survey instrument was used to survey occupants in other office buildings under other survey projects. The number of responses represents a large enough population to establish “normal” responses to these questions. The normative responses presented in the table were obtained from the responses of 1,259 office workers, occupying 13 different office buildings, covering a range of lighting installations of various ages. We chose the instrument because it had these normative values which we use for comparing our results to other’s findings of responses to the same questions over a wide range of conditions.

Question	Normative Response (ave. % agree)
Overall, the lighting is comfortable.	69%
The lighting helps me to focus on my work.	none
The lighting is uncomfortably bright.	16%
The lighting is uncomfortably dim.	14%
The light fixtures themselves are too bright.	14%
There is too much light in some areas; not enough in others.(The lighting is poorly distributed)	25%
The lighting causes deep shadows.	15%
Reflections from the light fixtures sometimes hinder my work.	19%
Skin tones look unnatural under this lighting.	9%
It is difficult to distinguish shades of color under this lighting.	none
The lights sometimes flicker or hum annoyingly.	4%
How does the lighting compare to similar workplace in other buildings.*	4.1

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

Table 27. Lighting Quality Responses and Normative Responses

The responses, by site, to the first, third, fourth, and sixth question from Table 27 were compared to LPD measurements for the same sites, and the results were further examined to find a correlation to overall lighting comfort.

For each space type we compared overall occupant comfort (Question 1) to LPD. Occupant comfort for all three space types was higher than the passing criterion of 69%. Very few sites overall had comfort ratings below 70%. Although the results were consistently high, they did however fall into three distinct categories, referred to as “low”, “medium” and “high” overall lighting comfort. The categories are defined as:

Category	Percent Agree
low	<75%
medium	>75% and <100%
high	= 100%

With these distinctions, we can compare overall satisfaction responses to other questions to search for a correlation between overall comfort and other comfort indicators. Sites with “low” comfort ratings are discussed in detail in Section F.3 .

5.1.1 Office

The office lighting quality analysis was based on measurements of the open office space at 25 office buildings. Seven of the spaces had task lighting although the occupant responses for those sites did not vary significantly from the other spaces without task lighting. For simplicity, we have not distinguished these sites in our presentation of results.

The results from the questionnaire were tallied and are presented in Table 28. The questions in bold text in the table are those that were analyzed in detail and discussed in Appendix F.

Overall, most occupants were satisfied with the lighting quality. The results indicate that the satisfaction in these spaces is higher than the normative data for all questions, except the sixth question, which deals with lighting uniformity. The level of uniformity, gauged by the sixth question, “There is too much light in some areas; not enough in others”, had the most variation in response (0 - 67% response range). The relatively high average response (31%) suggests that many sites had non-uniform lighting as perceived by the occupants.

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

* Bold text indicates more detail provided.

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

Table 28. Lighting Quality Responses for Offices

5.1.2 Retail

The retail lighting quality analysis was based on measurements of the sales area of 27 retail stores. The results from the questionnaire are presented in Table 29.

Overall, most occupants were satisfied with the lighting quality. The level of uniformity, gauged by the sixth question, “There is too much light in some areas; not enough in others”, had the most variation in response (0 – 100% response range). The large variation and the relatively high average response (33%) suggest that many sites had non-uniform lighting.

Question*	Average % agree	Range of Responses
Overall, the lighting is comfortable.	92%	55% to 100%
The lighting helps me to focus on my work.	89%	64% to 100%
The lighting is uncomfortably bright.	5%	0% to 30%
The lighting is uncomfortably dim.	9%	0% to 45%
The light fixtures themselves are too bright.	5%	0% to 45%
There is too much light in some areas; not enough in others.	33%	0% to 100%
The lighting causes deep shadows.	13%	0% to 55%
Reflections from the light fixtures sometimes hinder my work.	18%	0% to 71%
Skin tones look unnatural under this lighting.	17%	0% to 57%
It is difficult to distinguish shades of color under this lighting.	12%	0% to 40%
The lights sometimes flicker or hum annoyingly.	18%	0% to 60%
*How does the lighting compare to similar workplace in other buildings.***	4.89	4.00 to 6.00
Number of respondents/site(n)	9	1 to 20

* Bold text indicates more detail provided.

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

Table 29. Lighting Quality Responses for Retail

5.1.3 Classroom

The classroom lighting quality results are based on measurements of general classrooms at 21 schools.

The occupant satisfaction questionnaire was distributed to teachers. The results from all twelve questions are presented in Table 30. Overall, most teachers were satisfied with the lighting quality. They expressed the most concern with reflections from the light fixtures (Q8) and light fixture flickering and humming (Q11) as indicated by the large variation in responses (0 - 75%, and 0 - 70% response range, respectively). However, these appear to be fairly low concerns given the overall comfort average response of 91%. The graphs in Appendix E provide additional detail on occupant comfort and satisfaction.

Question*	Average % agree	Range of Responses
Overall, the lighting is comfortable.	91%	67% to 100%
The lighting helps me to focus on my work.	85%	50% to 100%
The lighting is uncomfortably bright.	7%	0% to 33%
The lighting is uncomfortably dim.	9%	0% to 25%
The light fixtures themselves are too bright.	4%	0% to 25%
There is too much light in some areas; not enough in others.	20%	0% to 67%
There is not enough light for the students to see what I am doing.	4%	0% to 20%
Reflections on the white board or computer screens are sometimes a problem.	38%	0% to 75%
Skin tones look unnatural under this lighting.	12%	0% to 33%
It is difficult to distinguish shades of color under this lighting.	6%	0% to 16%
The lights sometimes flicker or hum annoyingly.	22%	0% to 70%
*How does the lighting compare to similar workplace in other buildings.***	4.72	3.82 to 6.00
Number of respondents/site(n)	12	4 to 19

* Bold text indicates more detail provided below.

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

Table 30. Lighting Quality Responses for Classrooms

5.2 Quality Assessment Findings

This section present the findings by lighting power density and by illuminance uniformity. The graphs illustrate that the respondents in general thought the lighting in the space was comfortable, regardless of LPD, suggesting a lack of correlation between LPD and occupant satisfaction. These results are significant in that they suggest that concerns about lighting quality suffering as a result of reduced lighting power densities are misplaced.

5.2.1 LPD & Illuminance Results

The results from the lighting quality assessment measurements were correlated to space LPD. Lighting power densities were categorized as low, medium or high by space type according to the ranges in Table 31.

LPD		
Low	**Medium**	**High**
<1.0	1.0 - 1.75	>1.75
<1.5	1.5 - 2.5	>2.5
<1.0	1.0 - 1.75	>1.75

Table 31. LPD Distribution by Building Type

Figure 7 shows that there is a correlation between LPD and horizontal illuminance[10] levels. However, Figure 8, Figure 9 and Figure 10 show that there is no correlation between LPD and overall occupant comfort or illuminance levels and overall comfort. The comparison was also done at the building type level to investigate any trends. Results by building type are presented in Appendix F.

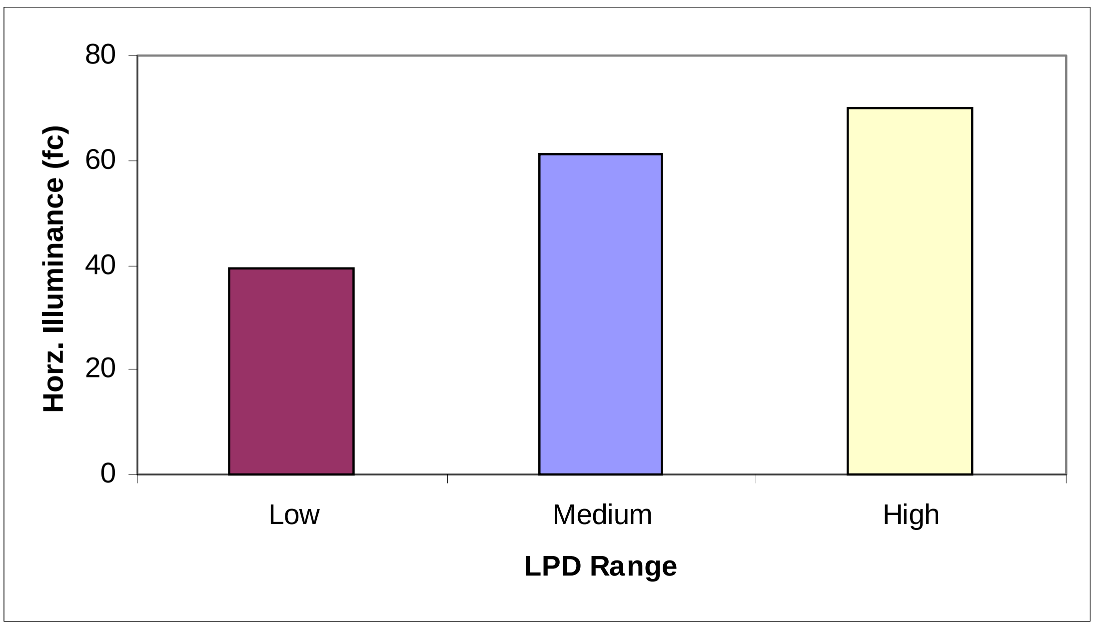

Figure 7. LPD - Horizontal Illuminance Comparison

[10] The "top" cubic measurement, as described in Chapter 3, was used for horizontal illuminance in all analyses.

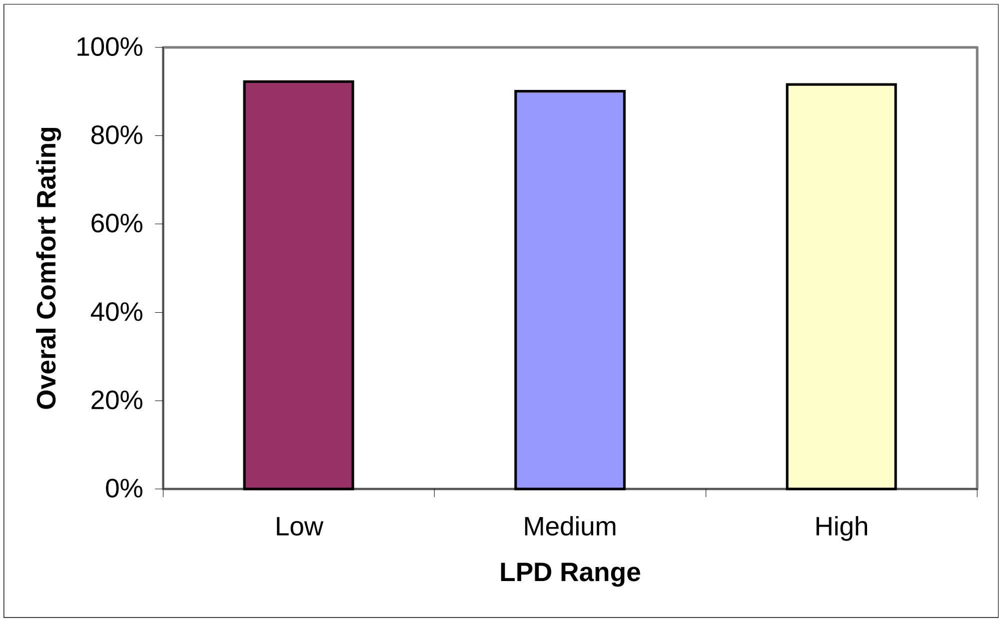

Figure 8. Overall Comfort vs. LPD Range

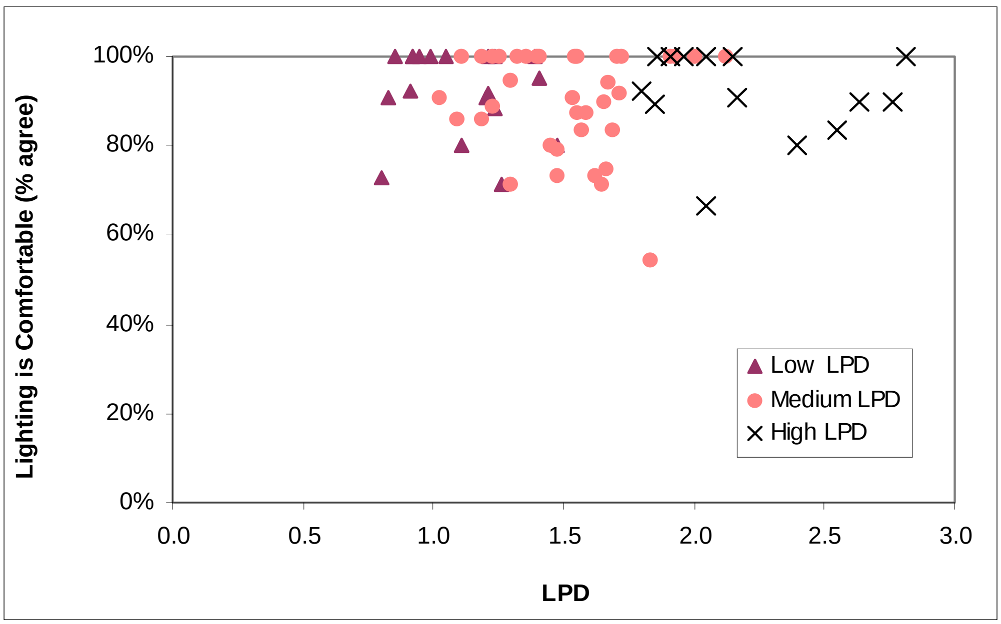

Figure 9. Overall Comfort vs. LPD

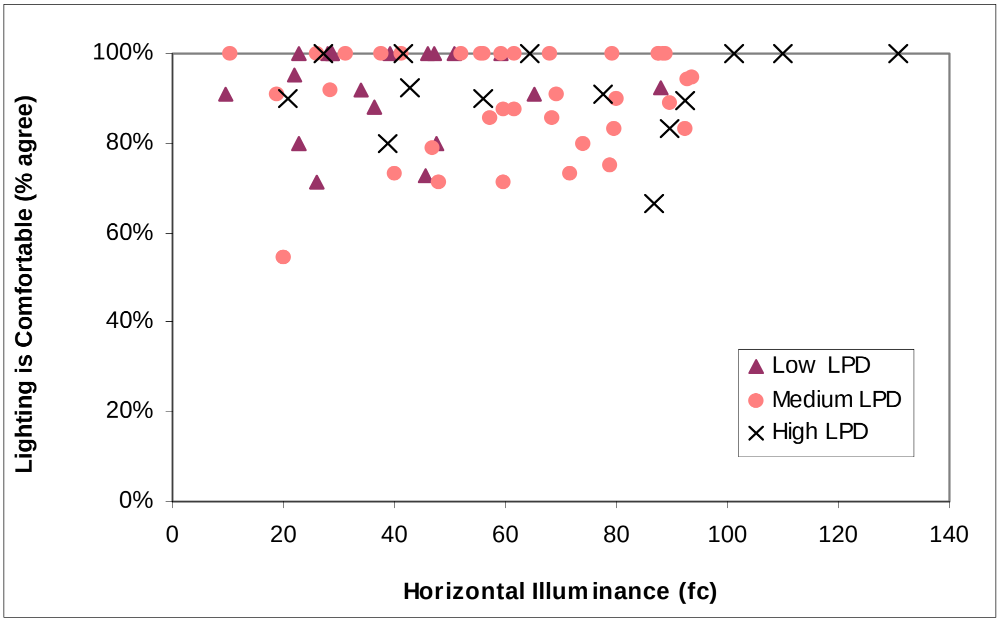

Figure 10. Overall Comfort vs. Horizontal Illuminance (with LPD Ranges)

5.2.2 Illuminance Uniformity Results

Illuminance uniformity is a quantity that describes lighting distribution. Unevenly distributed lighting can result in occupant discomfort.

We looked at occupants' perception of lighting uniformity vs. illuminance uniformity based on photometric measurements. Illuminance uniformity is calculated from the photometric measurements as the minimum horizontal illuminance measurement in the space divided by average horizontal illuminance. As mentioned previously, at least six measurements were made within each space. An illuminance uniformity value of 1.0 indicates that there is no variability in the measured illuminance. Therefore, it would be expected that as uniformity increases toward 1.0 the percent of respondents who agree that the lighting is non-uniform would go to zero (0). As shown in Figure 11 this is clearly not the case, suggesting that occupant perceptions and satisfaction levels are complex responses to more factors than actual lighting conditions.

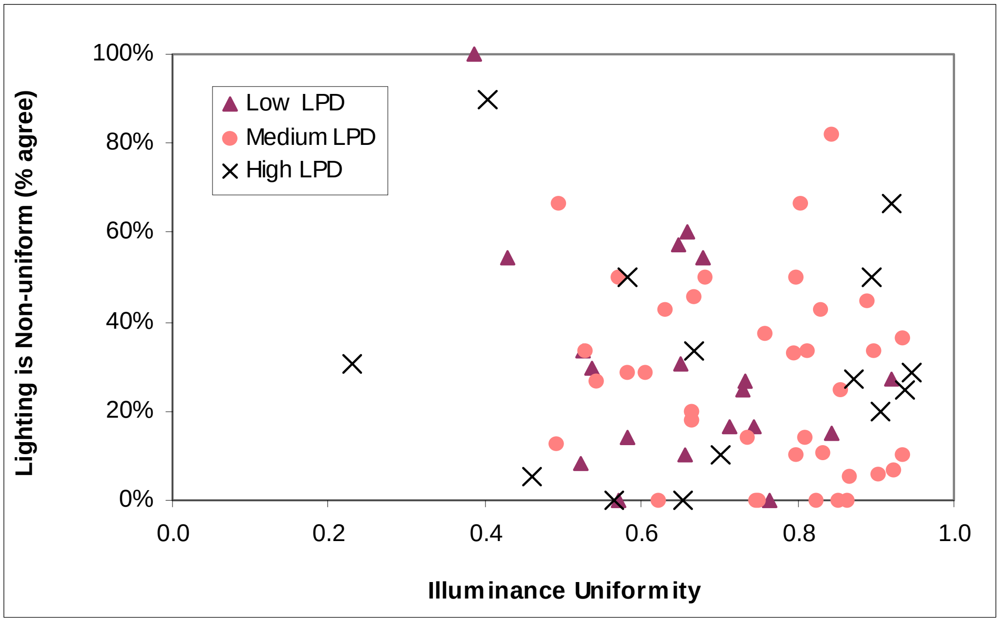

Figure 11. Occupants' Perception of Lighting Uniformity vs. Measured Illuminance Uniformity

Figure 12 shows occupants' overall comfort and satisfaction compared to measured illuminance uniformity, also showing no clear correlation between comfort and lighting uniformity. Figure 13 presents the measured illuminance uniformity compared to LPD. This graph simply consolidates the measurements by LPD ranges (described in Table 31) presented in the scatter plots.

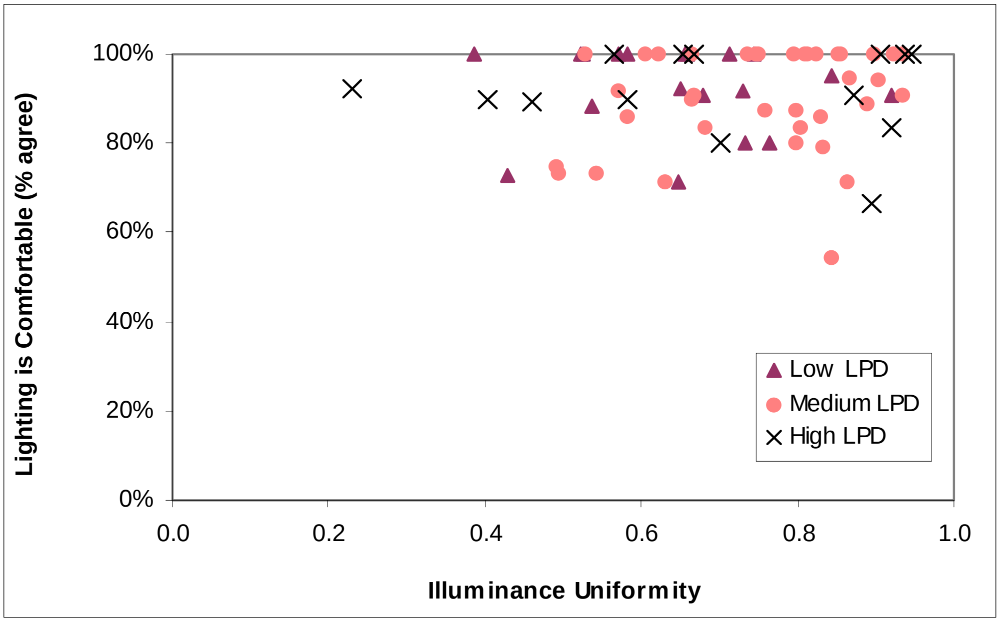

Figure 12. Overall Comfort vs. Illuminance Uniformity

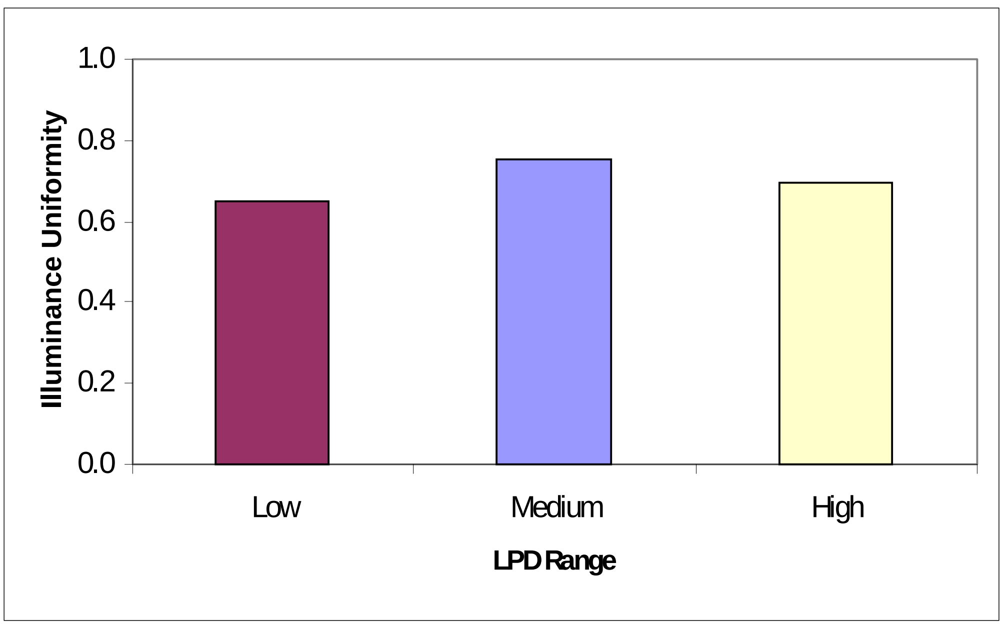

Figure 13. Measured Illuminance Uniformity by LPD Range

The comparisons were also done at the building type level to investigate any trends. Results by building type are presented in Appendix F.

5.2.3 Lighting Quality Assessment Summary

Our analysis shows that there is virtually no correlation between lighting quality and occupant comfort. 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). The comparison was also done at the building type level to investigate any trends. In all cases, there was no clear correlation.

These results suggest that concerns about lighting quality suffering as a result of reduced lighting power densities are misplaced. Lighting quality is known to be a function of a variety of design considerations, such as light distribution, brightness ratios and color rendering, 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 deeper 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.

However, several observations can be made from our analysis:

- Overall occupant comfort for all spaces was higher than the passing criterion.
- 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 actual lighting conditions.
- Occupants often perceived the space lighting to be non-uniform, however non-uniform lighting does not necessarily cause discomfort or dissatisfaction.

APPENDIX A. SCREENING AND SCHEDULING INSTRUMENT

CALL FORM

Site ID_______________

Record Company and Project Name:_________________________________
Verify these. If different record here:__________________________________
If the name has changed, do not schedule the on-site survey at this time, but continue with questions.

I am part of a team that is conducting a study of lighting energy efficiency for the California Public Utilities Commission[11]. We received your name because you participated in a previous utility evaluation study, conducted between 1996 and 1999. We would appreciate a revisit your building to gather some additional information on its lighting system and lighting quality.

In order to make our study successful, we need to be confident that the lighting system, and the use of the space, has not changed. Therefore, we need to ask you the following questions:

1. Our records show that the building was built in _________. Is this correct? *If **NO** ask them for correction (enter here _____________) and continue with questions. DO NOT SCHEDULE the on-site survey at this time.*
2. Our records show that the building is located at _____________________. Is this correct? *If **NO** ask them for correction (enter here ________________) and continue with questions. DO NOT SCHEDULE the on-site survey at this time.*
3. Have there been any remodels or alterations to the LIGHTING SYSTEM since the building was completed? Yes No.
   If yes, describe____
4. Have there been any alterations or remodels to the SPACES WITHIN THE BUILDING that affect the lighting system? Yes No.
   (For example, addition of ceiling height partitions, additional switches. May need to probe somewhat to see if this does affect lighting)
   If yes, describe____
5. Have there been any changes in the OCCUPANCY or USAGE of your building? Yes No.
   If yes, describe____

[11] If respondent asks for more detail:
This is being done for the California Board for Energy Efficiency (or CBEE), which is part of the CPUC. The CBEE is refining its data on lighting energy efficiency practices in newly constructed buildings in California. Your building is part of a statistically representative sample of new buildings that is being used to monitor progress in lighting efficiency practices.

If they answer yes to questions 3,4 and 5, thank them for their time, and tell them we won't be conducting a follow-up survey, because we need buildings that have not changed since the previous survey. If you are unclear whether these answers constitute a drop, tell them you may be contacting them later. If they answer no to all of these questions, schedule an on-site survey.

Now that we've confirmed that your building is much the same as what was surveyed previously, I'd like to schedule a time when our surveyor can visit and make some additional measurements.

The follow-up site survey will take approximately 4 to 6 hours. During that time, our surveyor will be as unobtrusive as possible, mostly walking around the building counting light fixtures and making some floor area measurements. We will also need access to some of the light fixtures to verify specific lamp and ballast information and will bring our own ladder for this purpose. We will be taking some lighting measurements with hand-held equipment. We will hand out a brief postcard questionnaire to the occupants to get their assessment of the lighting quality at their work surface. This questionnaire will take about five minutes to complete.

In return for your cooperation on this survey, we will send you a brief report summarizing the information we have collected at your building. We expect this information should be very useful to your understanding of the efficiency and effectiveness of <u>your</u> lighting system.

(Proceed to propose a date for the survey, and gather all of the information needed to get the surveyor into the building.)

APPENDIX B. RE-SURVEY FORM

Site ID	96S27			**Site Name:**			
Space	**Original Surveyed Space**	**Current Surveyed Space**	**Fixture Code**	**Lamp Code**	**Description**	**Quantity of Each Fixture**	**Task or Track Lite**
14: Office - Other	12,000		CF18/CAP	CFC18W	Compact Fluorescent, Capsule, (1) 18W lamp		
			F43LL	F32T8	Fluorescent, (3) 48", T-8 lamp		
			F44LL	F32T8	Fluorescent, (4) 48", T-8 lamp (1 ballast)		
			I100/1	I100	Incandescent, (1) 100W lamp		
42: School shops	6,000		F42LL	F32T8	Fluorescent, (2) 48", T-8 lamp		
			F43LL	F32T8	Fluorescent, (3) 48", T-8 lamp		
			F44LL	F32T8	Fluorescent, (4) 48", T-8 lamp (1 ballast)		
			I100/1	I100	Incandescent, (1) 100W lamp		

Notes:

APPENDIX C. LIGHTING QUALITY QUESTIONNAIRES

OFFICE LIGHTING SURVEY

All of the statements below are about the **electric lighting** in your work area today.

Please indicate whether you agree or disagree with the statements numbered 1 through 11.

Y N 1. Overall, the lighting in this office is comfortable.

Y N 2. The lighting helps me to focus on my work.

Y N 3. The office is uncomfortably bright.

Y N 4. The office is uncomfortably dim.

Y N 5. The light fixtures themselves are too bright.

Y N 6. There is too much light in some areas; not enough in others.

Y N 7. The lighting causes deep shadows.

Y N 8. Reflections from the light fixtures sometimes hinder my work.

Y N 9. Skin tones look unnatural under this lighting.

Y N 10. It is difficult to distinguish shades of color under this lighting.

Y N 11. The lights sometimes flicker or hum annoyingly.

For question 12, circle the number.

12. How does the lighting compare to similar workplaces in other buildings?

worse		about the same				better
1	2	3	4	5	6	7

RETAIL LIGHTING SURVEY

All of the statements below refer to the **electric lighting** in this store today. Please indicate whether you agree or disagree with the statements numbered 1 through 11.

Y N 1. Overall, the lighting in this store is comfortable.

Y N 2. The lighting helps make the merchandise look appealing.

Y N 3. The store is uncomfortably bright.

Y N 4. The store is uncomfortably dim.

Y N 5. The light fixtures themselves are too bright.

Y N 6. There is too much light in some areas; not enough in others.

Y N 7. The lighting makes it difficult to examine detail closely.

Y N 8. Reflections on the merchandise are sometimes a problem.

Y N 9. Skin tones look unnatural under this lighting.

Y N 10. It is difficult to distinguish shades of color under this lighting.

Y N 11. The lights sometimes flicker or hum annoyingly.

For question 12, circle the number.

12. How does the lighting here compare to lighting in similar stores?

worse			about the same			better
1	2	3	4	5	6	7

CLASSROOM LIGHTING SURVEY

All of the statements below are about the **electric lighting** in this classroom today.

Please indicate whether you agree or disagree with the statements numbered 1 through 11.

Y	N	1. Overall, the lighting in this classroom is comfortable.
Y	N	2. The lighting helps the students to focus on classroom activities.
Y	N	3. The classroom is uncomfortably bright.
Y	N	4. The classroom is uncomfortably dim.
Y	N	5. The light fixtures themselves are too bright.
Y	N	6. There is too much light in some areas; not enough in others.
Y	N	7. There is not enough light for the students to see what I am doing.
Y	N	8. Reflections on white board or computer screens are sometimes a problem.
Y	N	9. Skin tones look unnatural under this lighting.
Y	N	10. It is difficult to distinguish shades of color under this lighting.
Y	N	11. The lights sometimes flicker or hum annoyingly.

For question 12, circle the number.

12. How does the lighting in this classroom compare to other classrooms?

worse			about the same			better
1	2	3	4	5	6	7

APPENDIX D. MEASUREMENT ERROR COMPARISONS

The graphs in this section show the comparisons for wattage, square footage and LPD by building type.

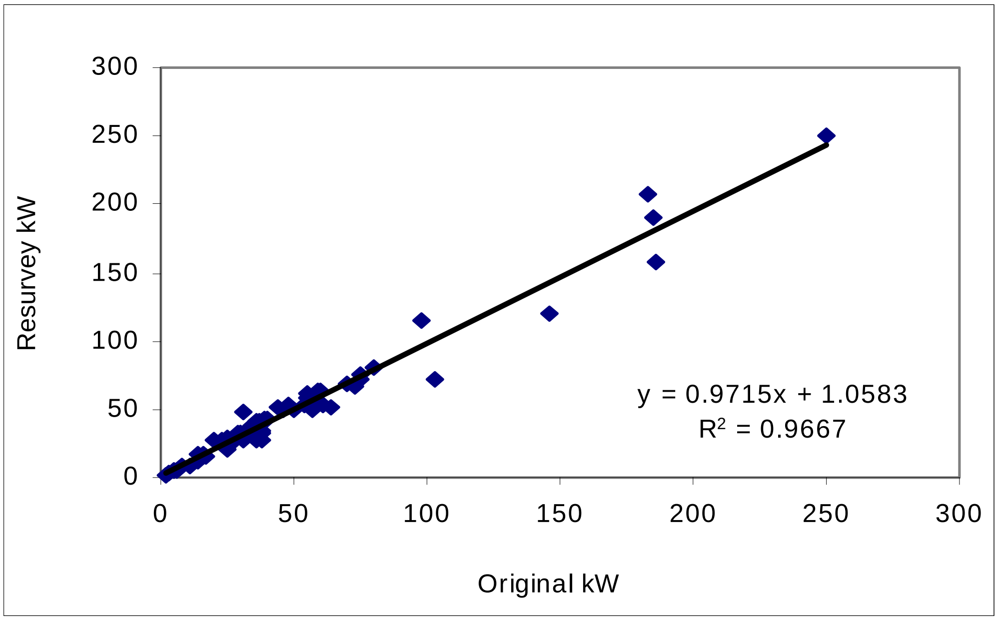

Figure 14. Overall kW Comparison

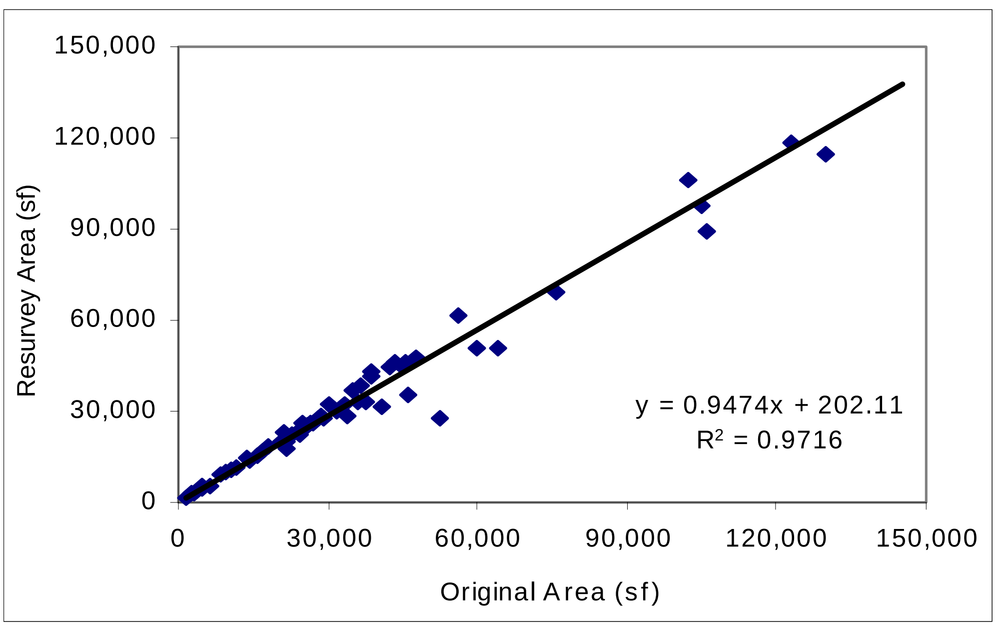

Figure 15. Overall Area Comparison

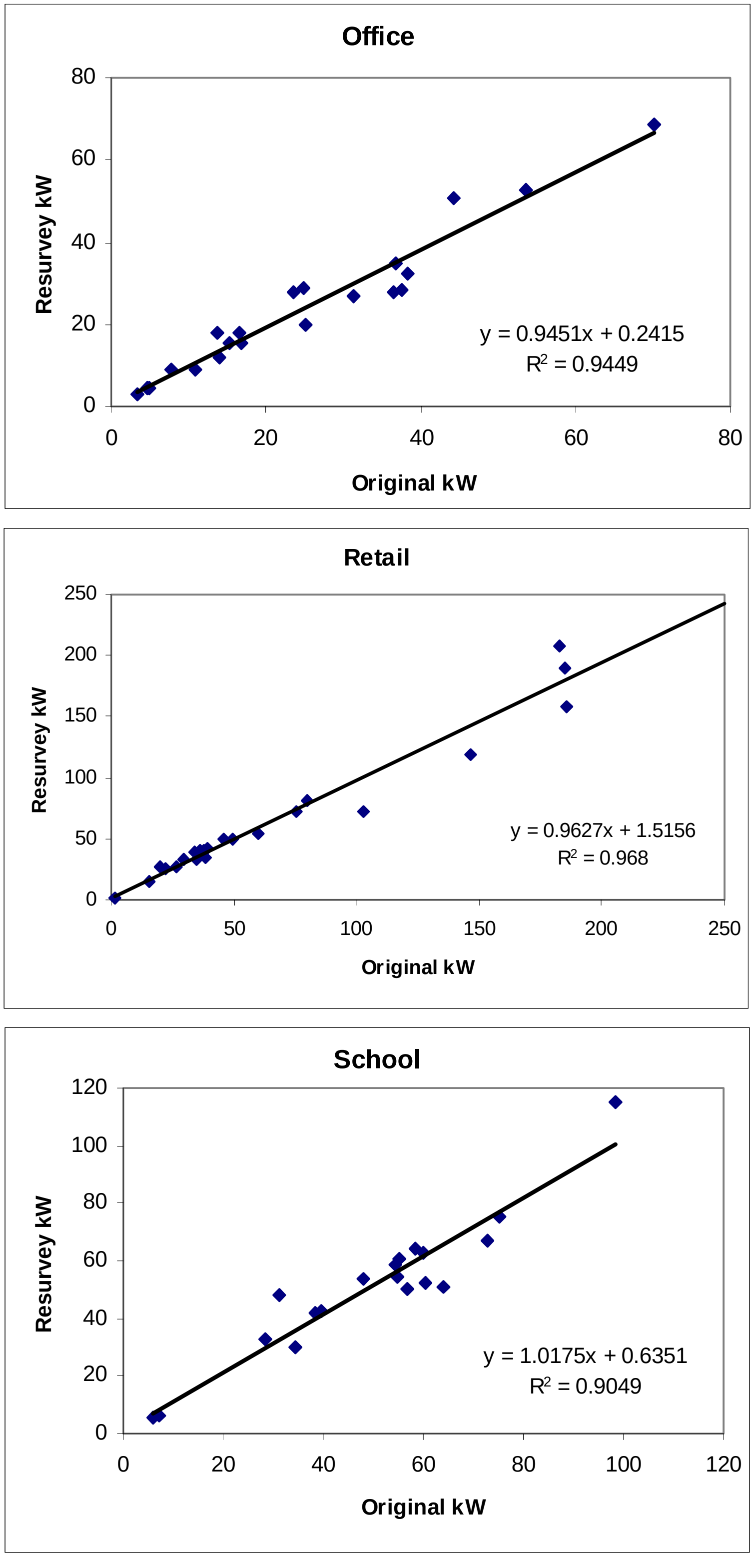

Figure 16. kW Comparison by Building Type

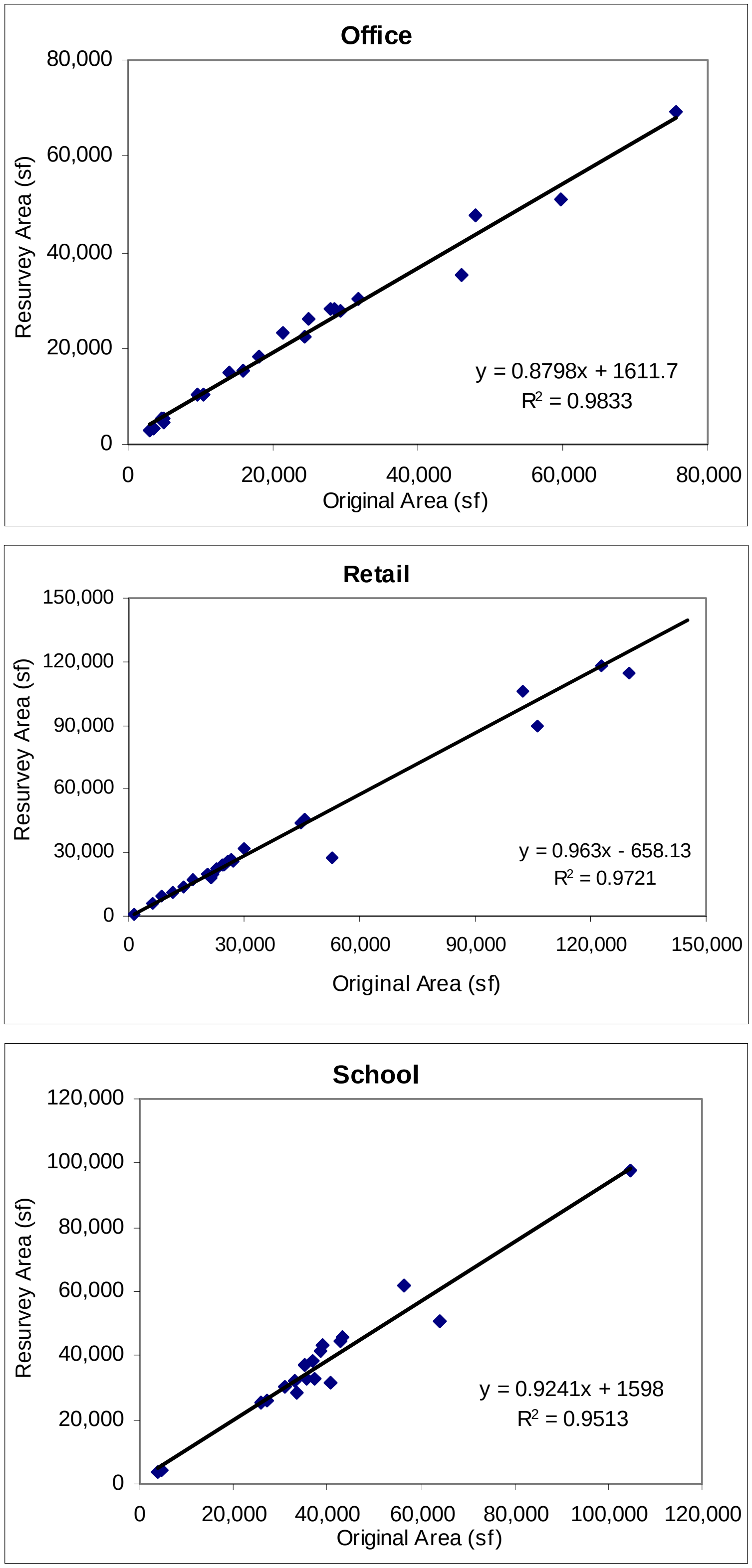

Figure 17. Area Comparison by Building Type

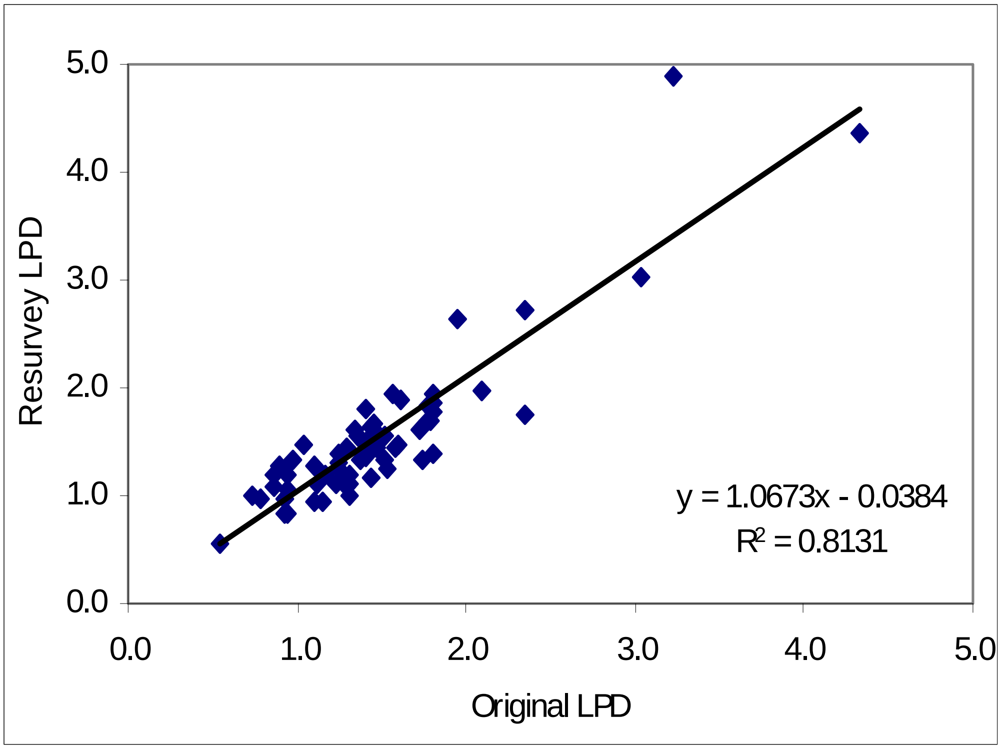

Figure 18. Overall LPD Comparison

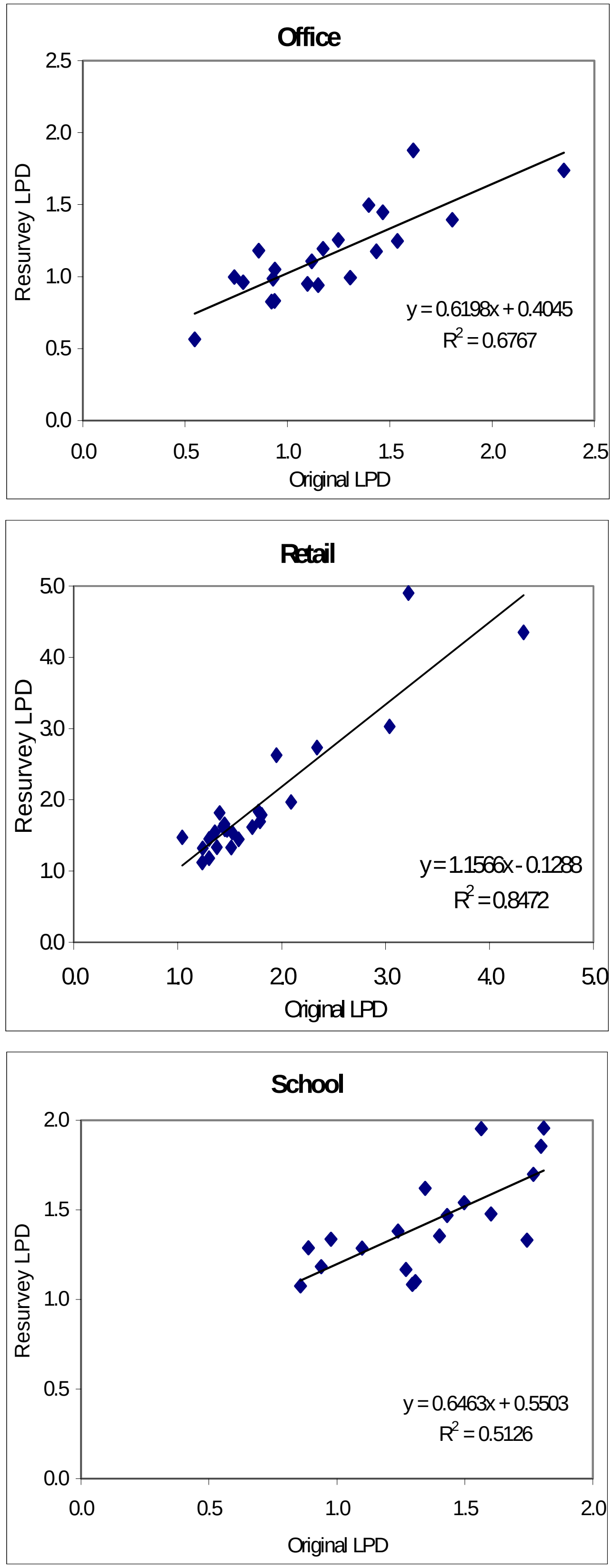

Figure 19. LPD Comparison by Building Type

APPENDIX E. STATISTICAL DETAILS - STRENGTH OF ASSOCIATION BETWEEN MEASUREMENTS

In the measurement error analysis, we have focused on looking for a systematic bias between the original and new measurements. Of course, bias is only one aspect of the accuracy of the measurements. A second important issue is the strength of the association between the original and new measurements. In other words, how accurately can the new measurements be predicted from the original measurement for individual buildings.

The strength of association is measured using a parameter called the error ratio. The error ratio is the standard deviation of the difference between actual and predicted value expressed as a percentage of the predicted value. Assuming a normal distribution, the probability is about 2/3 that the difference will be less than one standard deviation. An error ratio close to zero indicates a strong association. In this case, the second measurement is accurately predicted from the first variable. If the error ratio is close to zero, we can conclude that there is little measurement error.

In this context, it is important to understand the difference between an error ratio and a relative precision. An error ratio reflects variation in a characteristic of a building from one building to another building throughout a population. A relative precision reflects the variation we would expect in a sample statistic such as a ratio from one sample to another sample throughout the 'population' of all possible samples. Because of the laws of averages, we expect the relative precision (based on n sites) to be smaller that the error ratio. An error ratio measures a somewhat complex characteristic of a population – the strength of association between two measurable quantities eg lighting measured in the two surveys.

It is important to note that factors other than measurement error can contribute to the error ratio. For example, any actual differences in the connected lighting or area between the two surveys will tend to raise the error ratio.

Table 32 shows the error ratios for the key pairs of variables, for each of the categories considered. The first two columns of results are error ratios relating the original and new measurements of lighting connected Watts and area, respectively. Considering all buildings combined, the error ratio between the new lighting load and the original lighting load was found to be 14%. The error ratio between the new area and the original area was found to be even smaller, ±11%. Similar results for Watts and area were found in most categories. These results suggest a fairly low amount of measurement error.

Error ratios can also be used to measure the strength of association between the connected lighting load and the area of the surveyed space within a given survey. In this case, the error ratio reflects the uniformity of the LPD from building to building. For example, an LPD error ratio of 30% would suggest that the probability is about two-thirds that the lighting load of a particular building is within ± 30% of the expected lighting load calculated from area of the building and the average LPD of the sample of buildings. This type of error ratio is relevant in our context because it helps to indicate whether measurement error is small or large compared to the variation in LPD itself.

The last two columns of Table 32 show the error ratios for the lighting power density both for the original survey and the new survey. For example, considering all buildings combined, the error ratio for the original LPD was found to be ±29%. This suggests that the probability is about two-thirds that the connected lighting load measured in the original survey will be within ±29% of the expected lighting load given the area of the space measured in the original survey and the average LPD in the sample. This indicates that the error ratio of LPD is substantially smaller than the error ratios of the measurements of connected lighting load and area. This suggests that sampling variability is a much more important factor than variation arising from measurement error.

We can also compare the LPD error ratios in the original and new surveys. If we observe that the later is found to be systematically smaller than the former, it would suggest that there was less random error in the wattage and area measurements in the new survey than in the original survey. This might be expected given that the new study was known to be a validation study and the surveyors were instructed to get the best measurements they could. Referring to the last two last two columns of Table 32 there does seem to be some indication of reduced LPD error ratios in the new survey compared to the original survey. However, the reduction in the error ratio seems to be quite small. This is another indication that the variation in LPD is dominated by actual differences between buildings rather than measurement error. It also suggests that the original survey results were nearly as accurate as the more carefully done re-survey results.

Category		Resurv. Watts vs Orig. Watts	Resurv. Area vs Orig. Area	Orig. LPD	Resurv. LPD
All Buildings		0.139	0.106	0.285	0.264
Type	Office	0.161	0.085	0.287	0.163
	Retail	0.129	0.113	0.158	0.185
	School	0.135	0.103	0.229	0.184
Size	Small	0.131	0.092	0.338	0.321
	Medium	0.142	0.113	0.251	0.219
LPD	Low	0.145	0.063	0.179	0.230
	Medium	0.130	0.080	0.261	0.215
	High	0.156	0.196	0.198	0.251

Table 32. Error Ratios for All Categories of Buildings

APPENDIX F. ENGINEERING DETAILS –RESULTS BY SPACE TYPE

F.1 LPD & Illuminance

Office Results

Figure 20 compares overall occupant satisfaction to LPD for offices. The graph illustrates that the respondents in general thought the lighting in the space was comfortable, suggesting the lack of a strong correlation between LPD and occupant satisfaction. However, the graph shows that sites with high LPDs (~>1.75) were "medium" or "high" comfort sites, suggesting that these sites are more comfortable than those sites with lower LPDs.

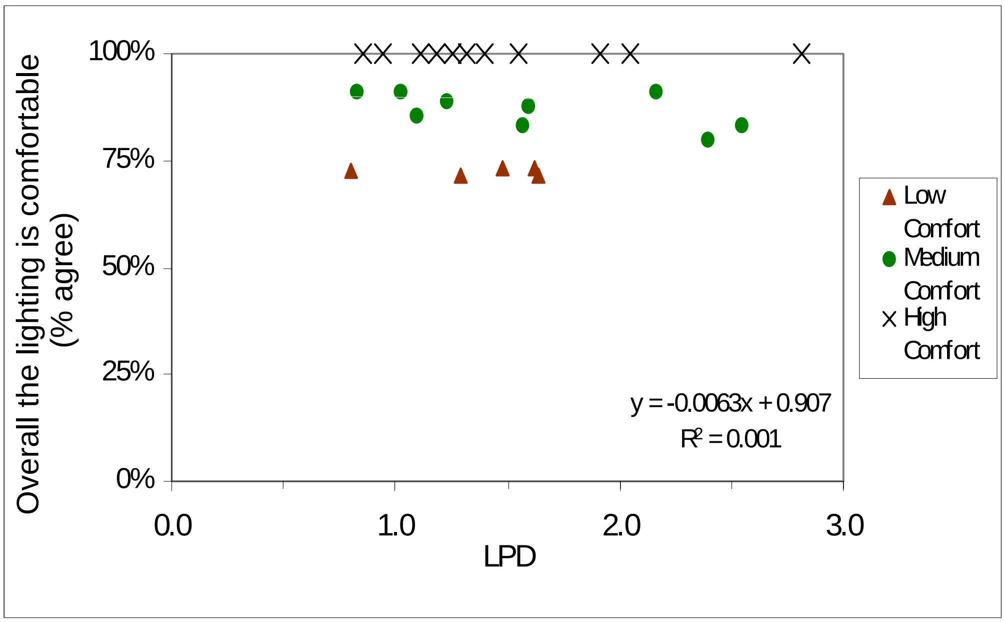

Figure 20. Office - Overall Comfort vs. LPD

Figure 21 presents overall comfort compared to average horizontal illuminance. As shown in the graph, the "high" and "medium" comfort sites cover a wide range of illuminance levels, indicating no strong correlation between comfort and horizontal illuminance. However, as with the LPD results, sites with relatively high horizontal illuminance levels (~ >70 fc) are "medium" or "high" comfort sites, suggesting that higher horizontal illuminance results in higher comfort.

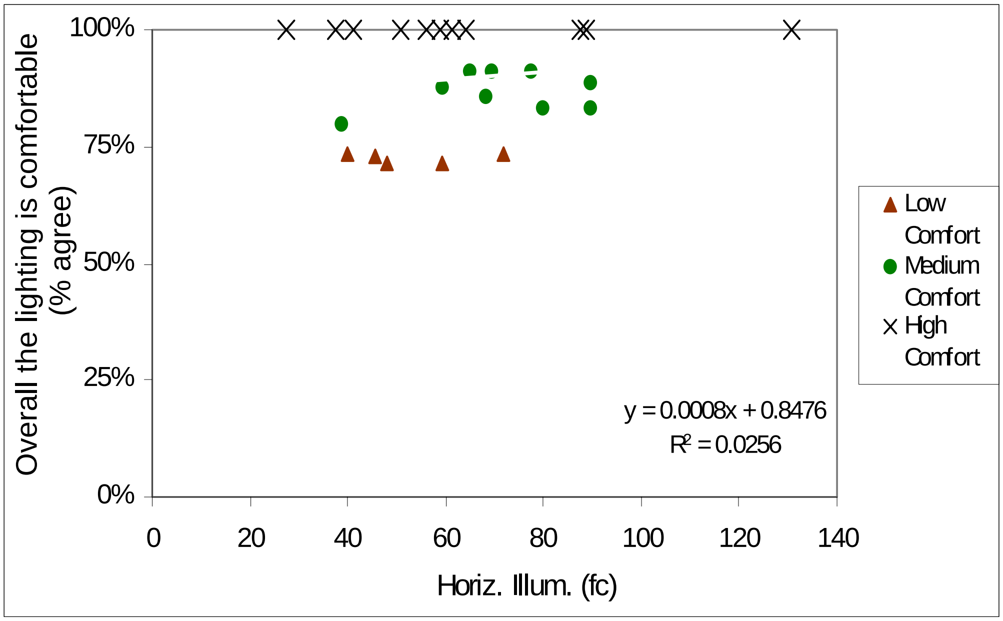

Figure 21. Office - Overall Comfort vs. Horizontal Illuminance

Figure 22 compares LPD to the percentage of respondents agreeing that the space was uncomfortably bright. In general, there is no correlation between brightness discomfort and LPD. Two sites had percent agreement greater than 30%. One was a low satisfaction site (36% agree) discussed in Section F.3. The other is a “high” comfort site with 33% of the respondents stating that the lighting is uncomfortably bright. The site is a very small office space with three survey respondents. The small sample size of respondents tends to skew the responses. Otherwise, the site received positive responses to the lighting quality questions.

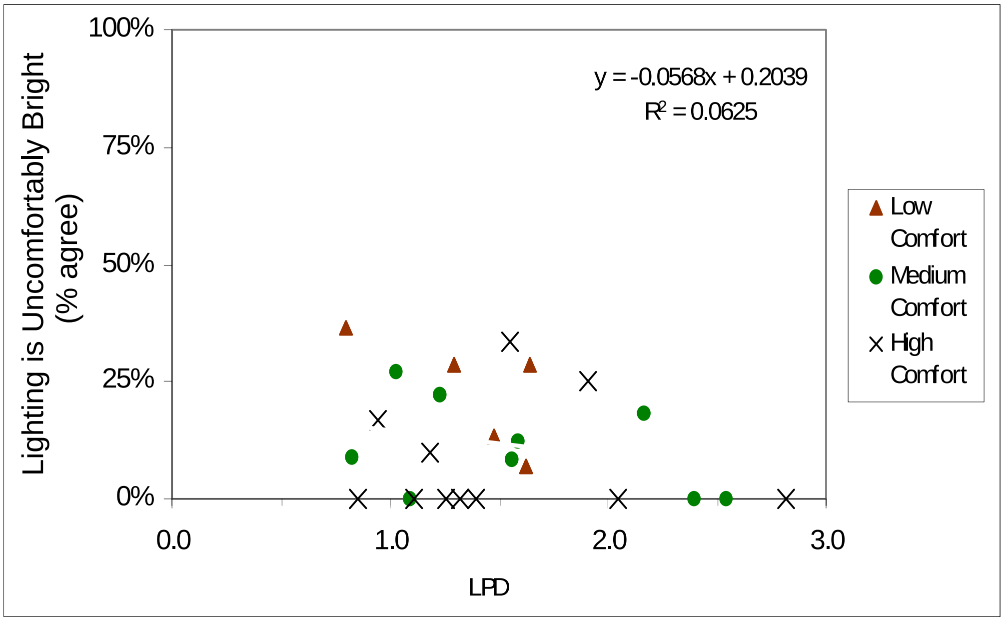

Figure 22. Office - Brightness vs. LPD

Figure 23 compares LPD to the percentage of respondents agreeing that the space was uncomfortably dim. The outlier in Figure 23 (response greater than 25% agree) is a “high” comfort site with 33% of the respondents stating that the lighting is uncomfortably dim. The site is a very small office space with three survey respondents. The small sample size of respondents tends to skew the responses. Otherwise, the site received positive responses to the lighting quality questions. (Please note, this is not the same site as the “uncomfortably bright” site discussed above.)

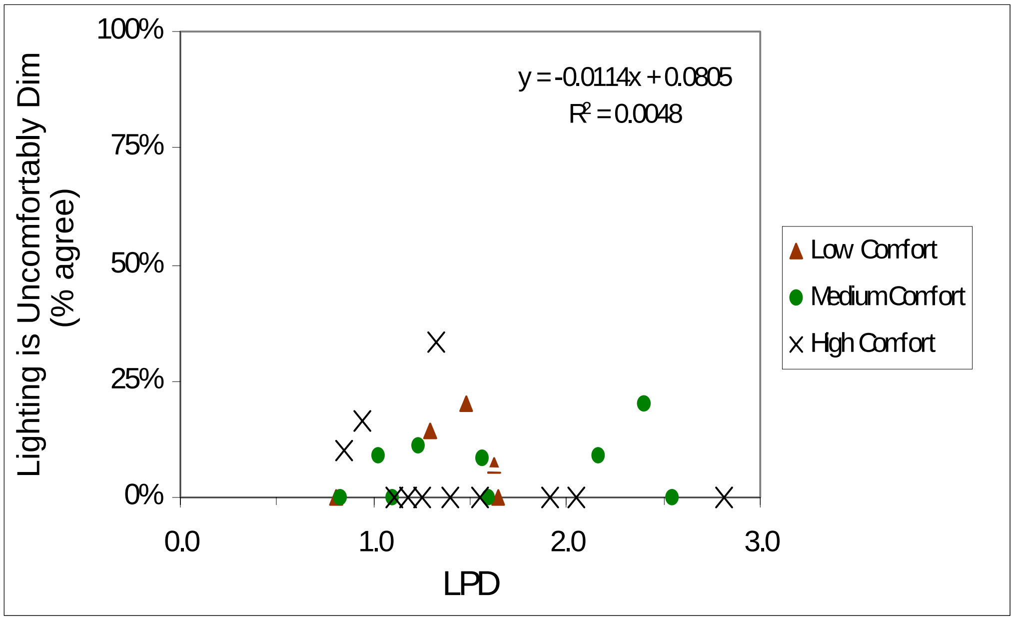

Figure 23. Office - Dimness vs. LPD

Retail Results

Figure 24 compares overall occupant satisfaction to LPD for retail. The graph illustrates that the respondents in general thought the lighting in the space was comfortable, regardless of LPD, suggesting the lack of a strong correlation between LPD and occupant satisfaction. However, the graph shows that sites with relatively high LPDs (~>1.80) were “medium” or “high” comfort sites, suggesting that these sites are more comfortable than those sites with lower LPDs.

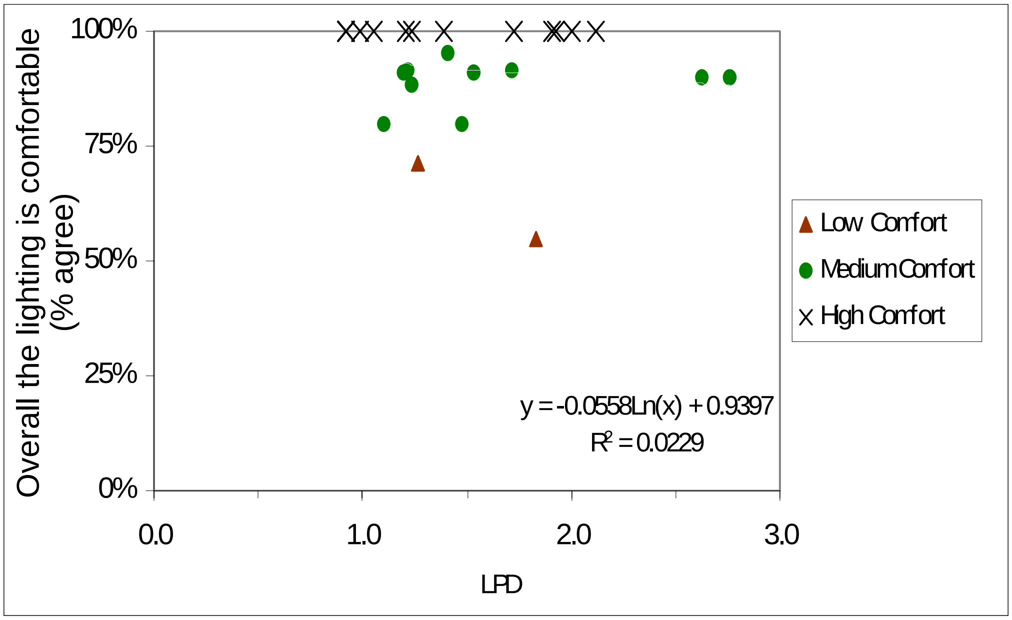

Figure 24. Retail - Overall Comfort vs. LPD

Because of the variability of illuminance levels in retail spaces, due primarily to the presence of merchandise-specific lighting, overall occupant comfort was also compared to horizontal and vertical illuminance[12] levels.

Figure 25 shows the comparison between overall comfort and average horizontal illuminance. Figure 26 shows the comparison between overall comfort and average vertical illuminance. As can be seen, overall comfort is not strongly correlated to either horizontal or vertical illuminance.

[12] Measured at the face of the merchandise shelves four feet off the ground.

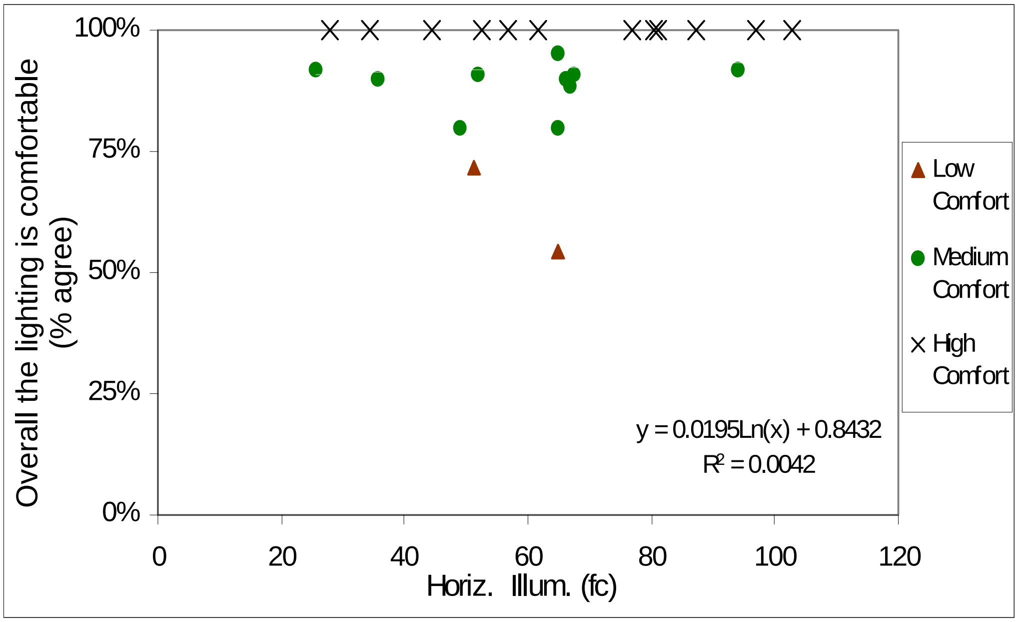

Figure 25. Retail - Overall Comfort vs. Ave. Horizontal Illuminance

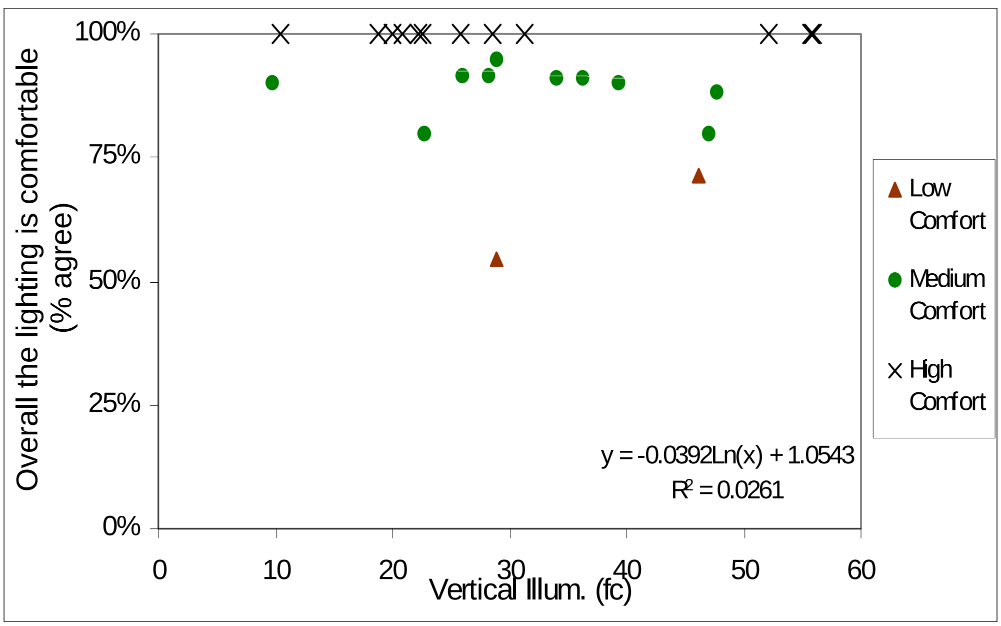

Figure 26. Retail - Overall Comfort vs. Ave. Vertical Illuminance

Figure 27 compares LPD to the percentage of respondents agreeing that the space was uncomfortably bright. A “medium” comfort site had a response of 30% agreement. This space has an LPD of 1.41 W/sf, average horizontal illuminance of 64.8 fc, and average vertical illuminance of 28.9 fc, none of which would indicate excessive brightness. All other sites had responses of less than 25%.

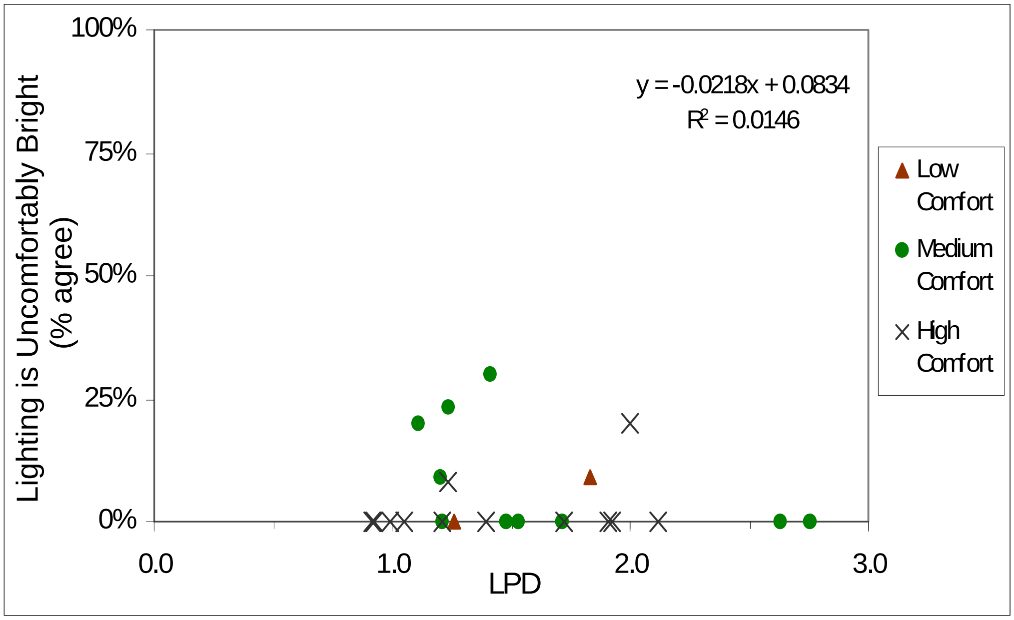

Figure 27. Retail - Brightness vs. LPD

Figure 28 compares LPD to the percentage of respondents agreeing that the space was uncomfortably dim. Two sites had responses greater than 25%. One is a “low” comfort site, which is described in Section F.3.2. The other is a “high” comfort site with 27% agreement. The site has an LPD of 1.91 W/sf, average horizontal illuminance of 76.8 fc, and average vertical illuminance[13] of 20 fc. The vertical illuminance is somewhat low, however, as seen in Figure 29, there are other sites with the same or lower illuminance that are not considered uncomfortably dim by the occupants. All other sites had responses of less than 25%.

[13] Measured at the face of the merchandise shelves four feet off the ground.

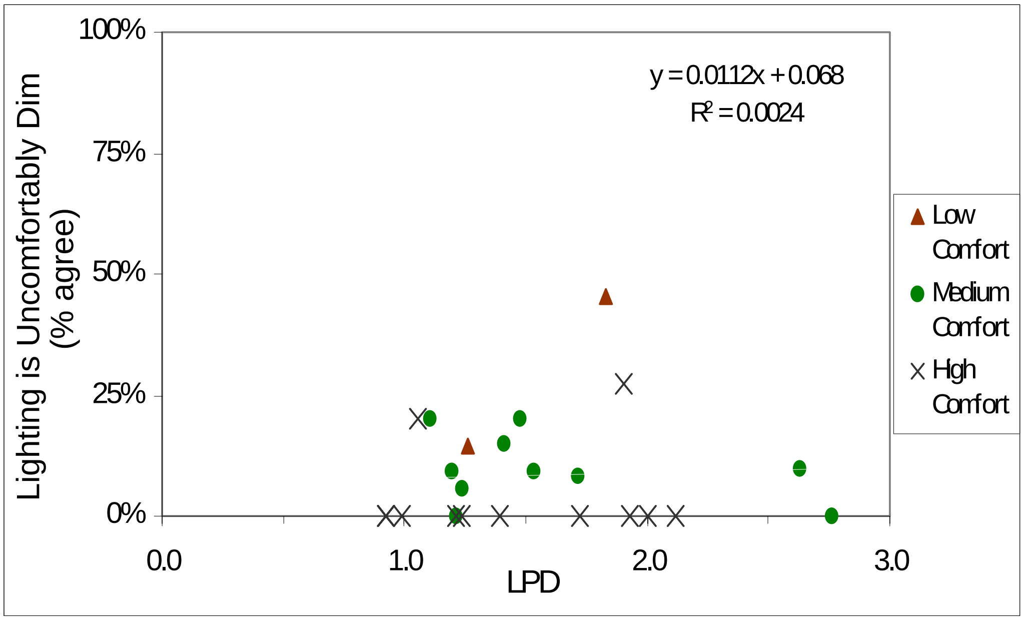

Figure 28. Retail - Dimness vs. LPD

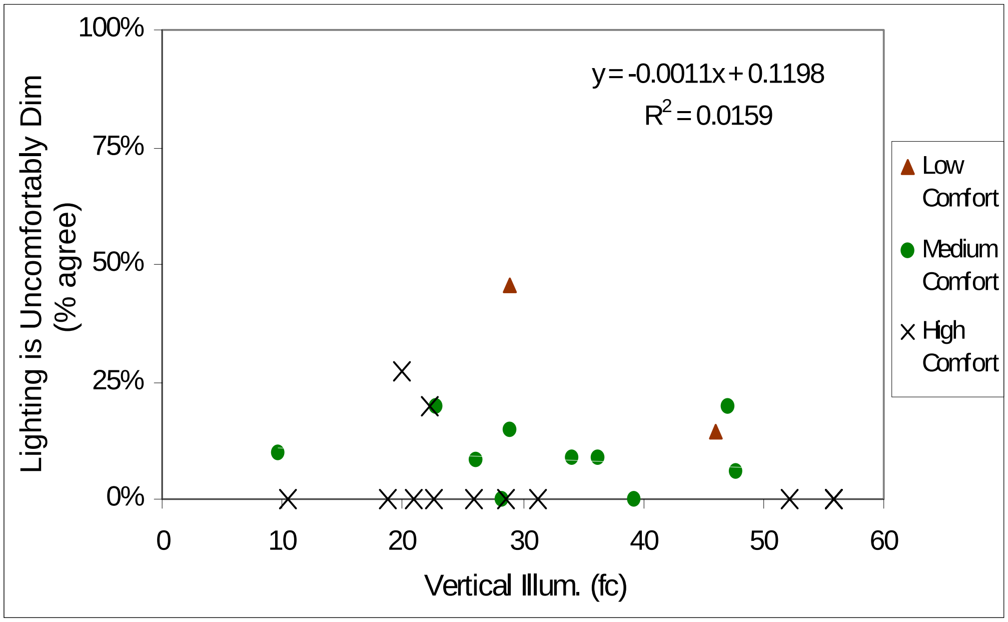

Figure 29. Retail - Dimness vs. Vertical Illuminance

Classroom Results

Figure 30 compares overall occupant satisfaction to LPD for classrooms. The graph illustrates that the respondents in general thought the lighting in the space was comfortable, regardless of LPD, suggesting a lack of correlation between LPD and occupant satisfaction.

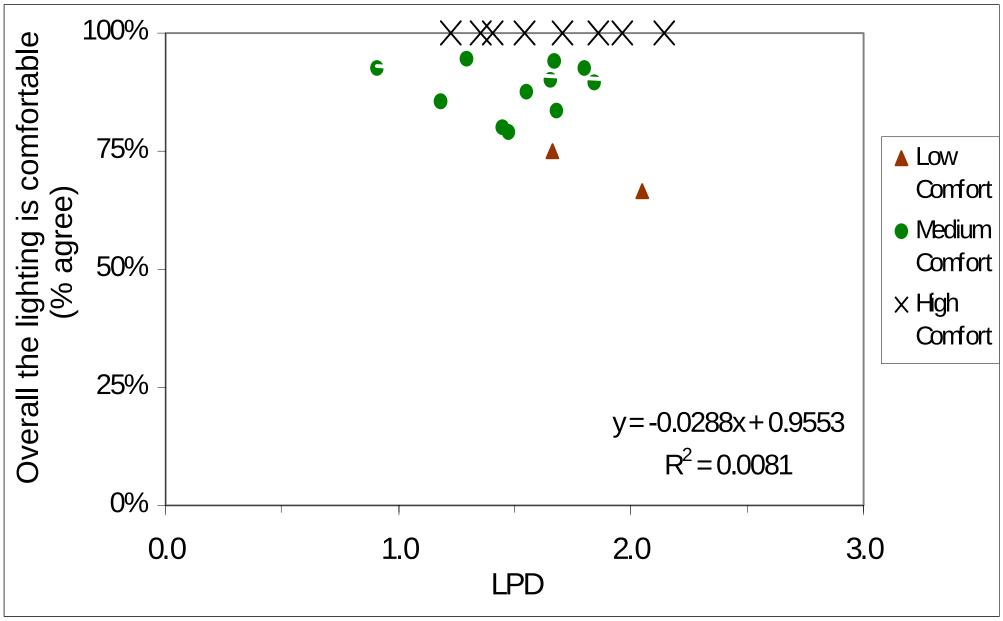

Figure 30. Classroom - Overall Comfort vs. LPD

Figure 31 compares LPD to the percentage of respondents agreeing that the space was uncomfortably bright. The only site with a relatively high "percent agree" response (33%) is a "low comfort" site discussed in Section F.3.3. No other sites had high "uncomfortably bright" ratings.

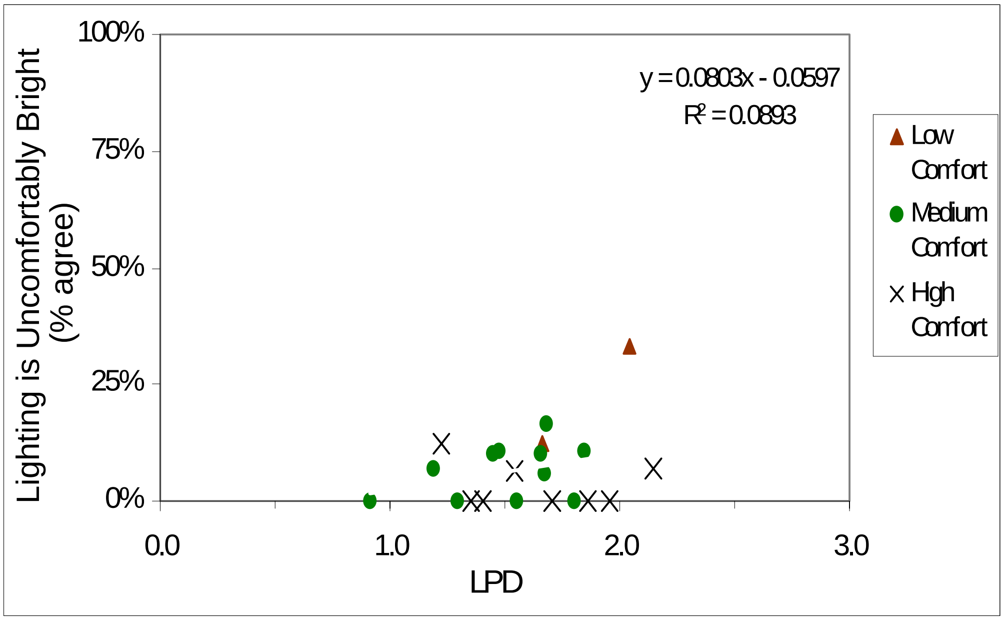

Figure 31. Classroom - Brightness vs. LPD

Figure 32 compares LPD to the percentage of respondents agreeing that the space was uncomfortably dim. Overall the responses were low, indicating that the classrooms are not too dim. Only one site, a "high comfort" site, had a response of 25% agreement. The classroom has an LPD of 2.0 W/sf and an average horizontal illuminance of 88 fc without daylighting. The site also had a relatively low ranking on light fixture flicker and hum (50%). Otherwise, the site received positive responses to the lighting quality questions.

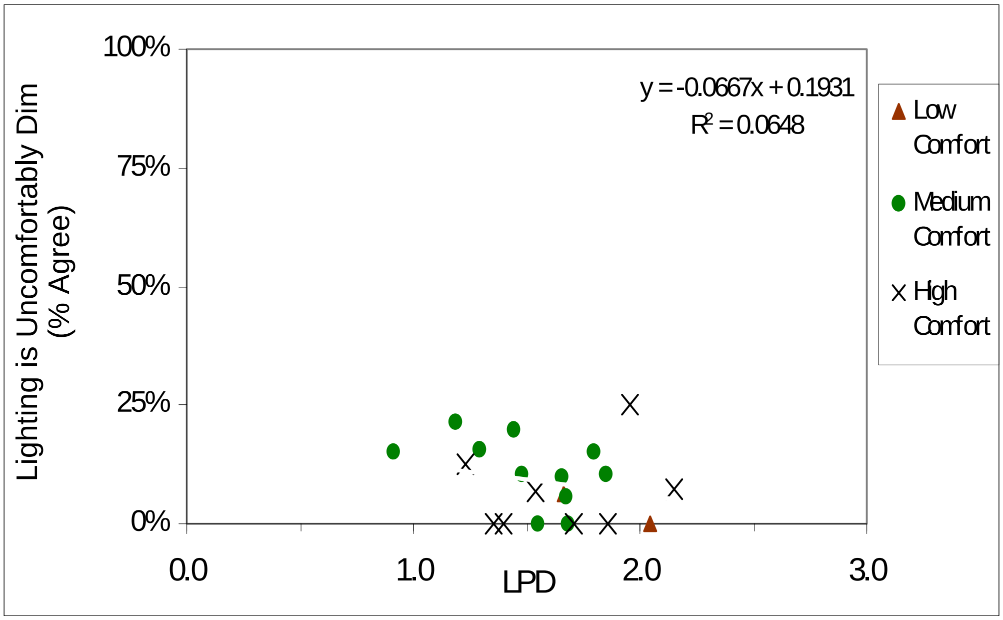

Figure 32. Classroom - Dimness vs. LPD

F.2 Illuminance Uniformity

Office Uniformity

Figure 33 presents the percent of respondents who agree with the statement "There is too much light in some areas; not enough in others" compared to LPD. The two "low comfort" sites with responses greater than 50% agree are discussed in Section F.3.1. The other site with a high percent agreement (67%) is a "medium comfort" site with non-uniform lighting according to the occupants. The survey responses indicate 100% disagreement with the uncomfortably bright, and uncomfortably dim statements meaning that the space is neither too bright nor too dim. The lighting uniformity based on photometric measurements is 0.92 indicating good uniformity. It is not apparent why the occupants consider this space uncomfortable.

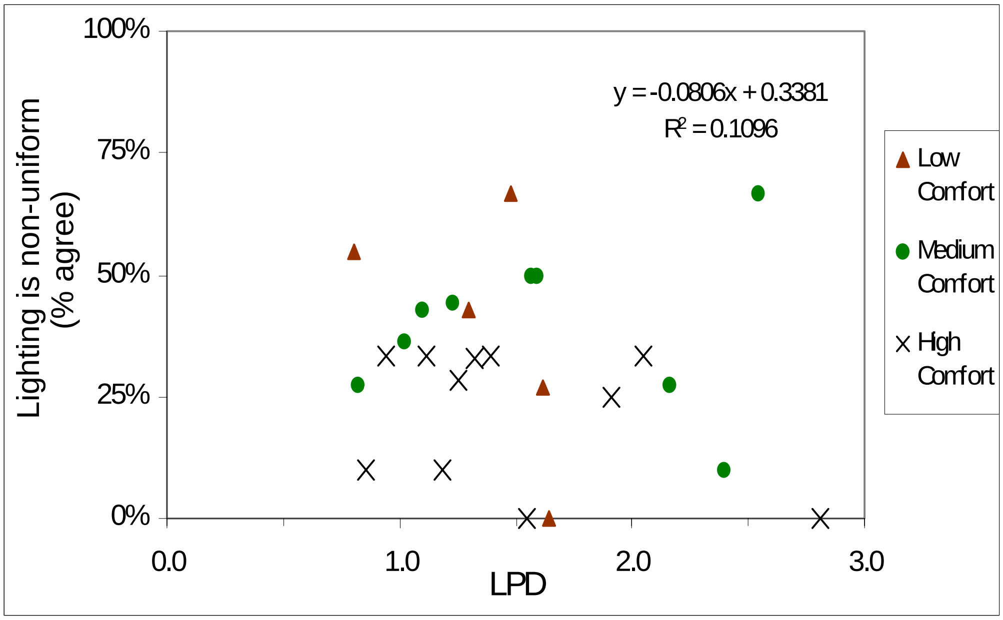

Figure 33. Office – Lighting Uniformity vs. LPD

Figure 34 shows occupants' perceptions of lighting uniformity vs. illuminance uniformity based on photometric measurements. The graph shows that there is no correlation between the occupants' perceptions of uniformity and the actual measured uniformity, suggesting that occupants' perceptions may be based on subtleties in the lighting or on other factors. The graph also shows that lighting comfort is not affected by illuminance uniformity. This result is also shown in Figure 35.

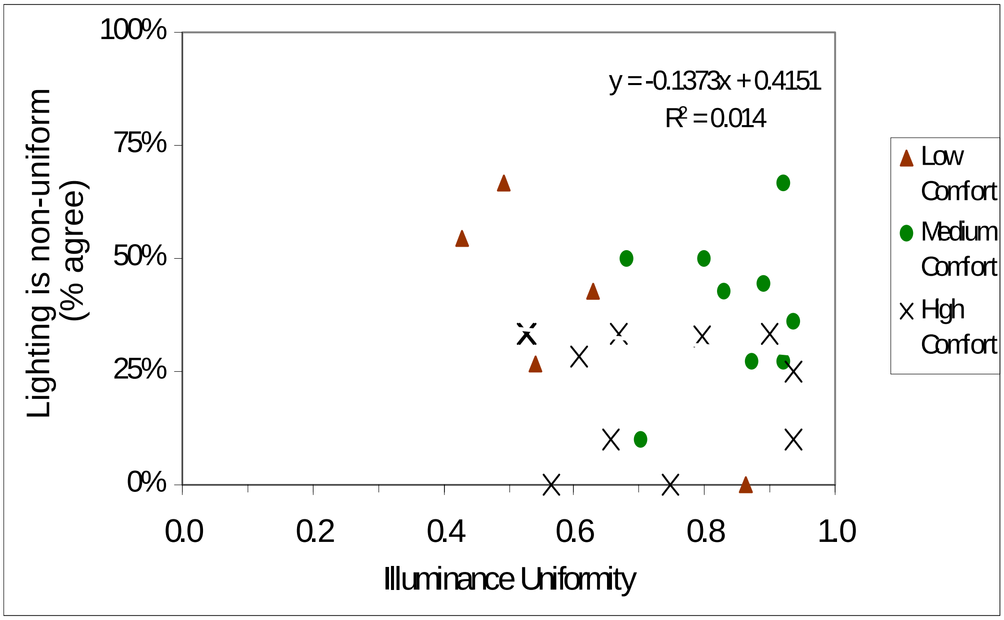

Figure 34. Office – Perception of Lighting Uniformity vs. Calculated Illuminance Uniformity

Figure 35 shows overall comfort compared to illuminance uniformity. There is a slight correlation in that the "low comfort" sites tend to have low uniformity values and the "medium" comfort sites tend to have higher uniformity values. However, the "high" comfort sites have uniformity values across most of the range, suggesting that there is no correlation between comfort and uniformity.

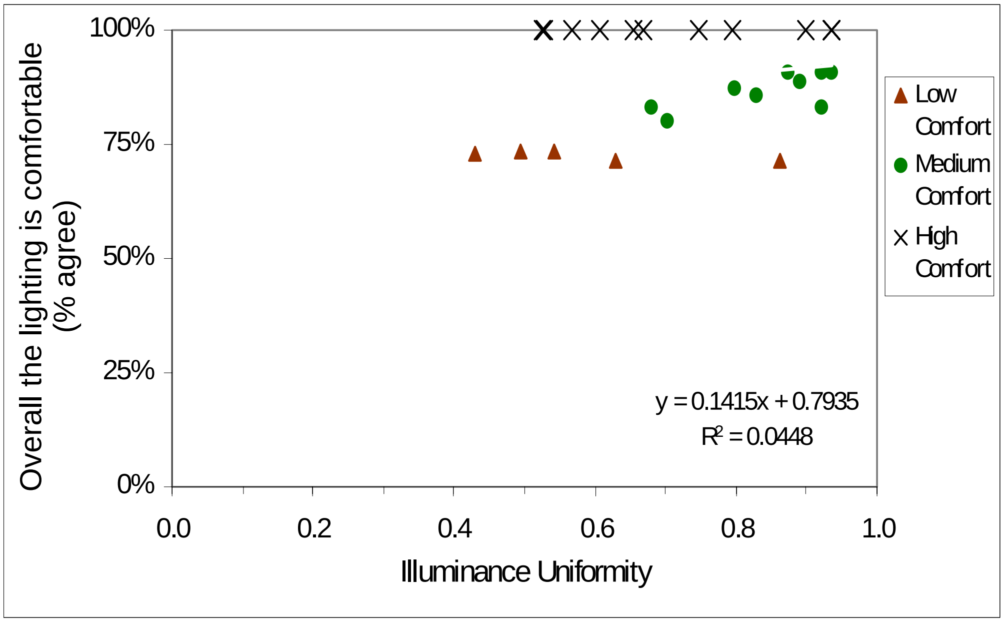

Figure 35. Office – Overall Comfort vs. Illuminance Uniformity

Retail Uniformity

Figure 36 presents the percent of respondents who agree with the statement “There is too much light in some areas; not enough in others” compared to LPD. Uniformity is a problem for several sites as indicated by a “percent agree” greater than 50%. For many of the sites it is the only unsatisfactory response. While the sites that have problems, tend to have uniformity problems, the graph shows that non-uniform lighting does not necessarily cause discomfort or dissatisfaction, as indicated by the scatter of “low”, “medium” and “high” comfort sites.

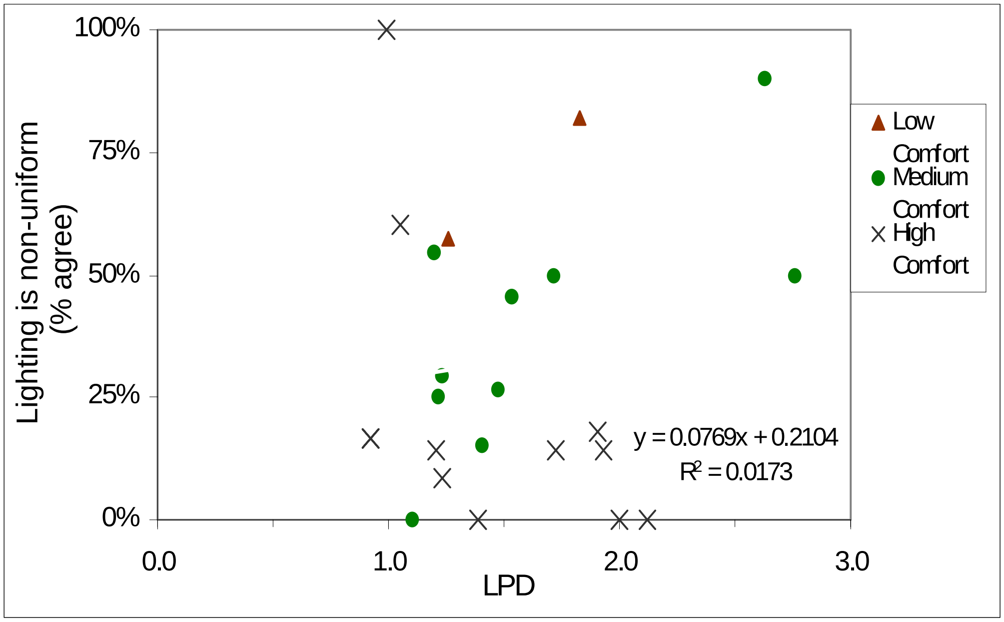

Figure 36. Retail – Uniformity vs. LPD

Figure 37 shows occupants' perception of lighting uniformity vs. illuminance uniformity calculated from photometric measurements. As shown in the graph, there is no correlation between perceived lighting uniformity and actual uniformity.

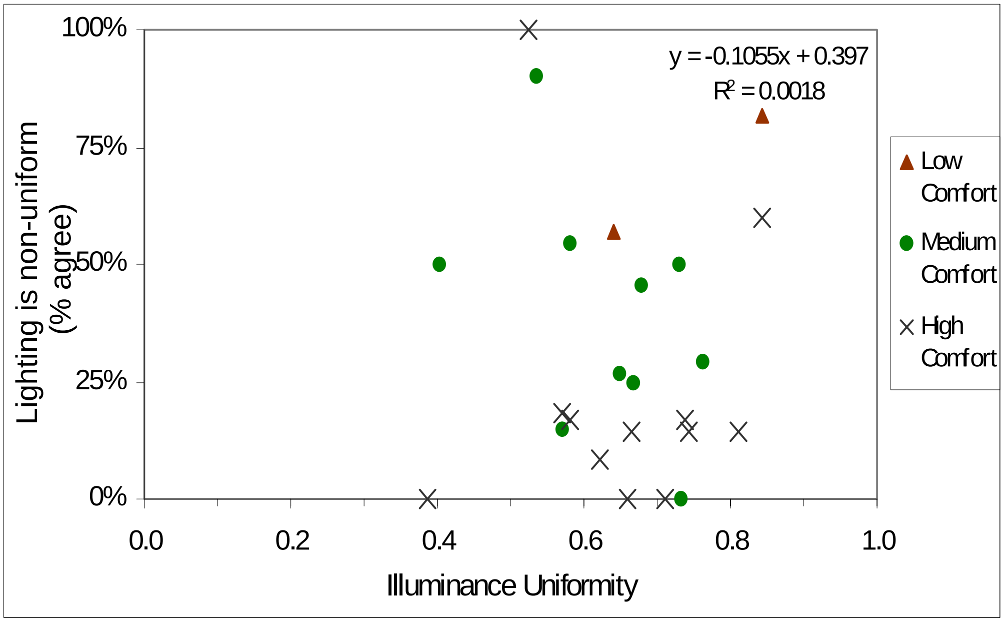

Figure 37. Retail – Perception of Lighting Uniformity vs. Calculated Illuminance Uniformity

Figure 38 shows overall comfort compared to illuminance uniformity. As indicated by the range of uniformity associated with “high” comfort sites, there is no correlation between comfort and uniformity.

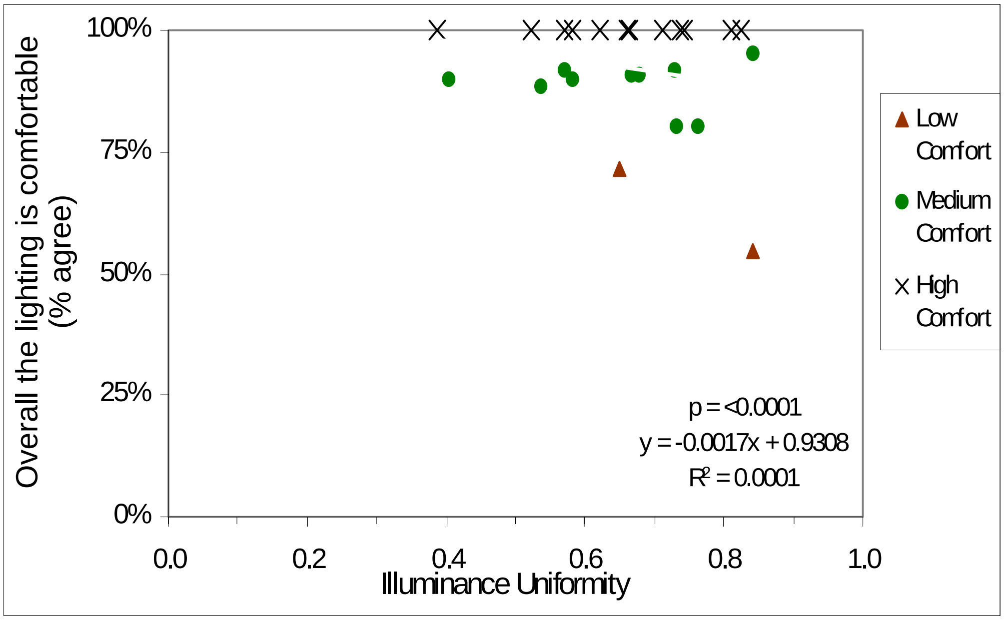

Figure 38. Retail – Overall Comfort vs. Illuminance Uniformity

Classroom Uniformity

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. To capture any irregularities in the results we also compared the satisfaction results to illuminance measurements without daylighting. No noticeable difference between the results was found.

Figure 39 presents the percent of respondents who agree with the statement “There is too much light in some areas; not enough in others” compared to LPD. One “medium comfort” site had a response greater than 50% agreement. This site also tended to have complaints about reflections on the boards. As can be seen by the scatter of “low”, “medium” and “high” comfort sites, there is no correlation between lighting uniformity and occupant comfort.

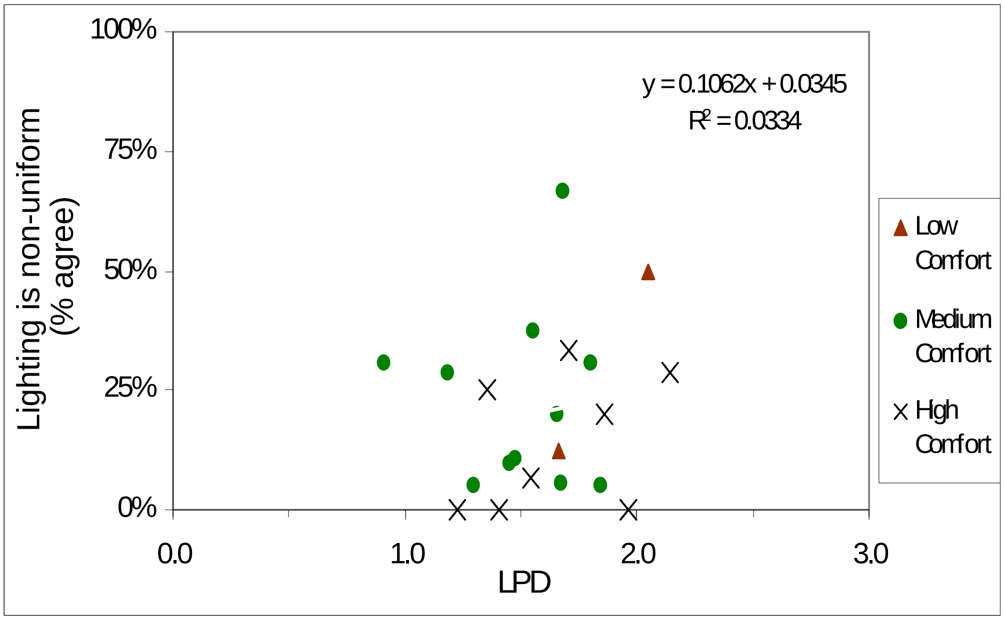

Figure 39. Classroom - Uniformity vs. LPD

Figure 40 shows occupants' perception of lighting uniformity vs. illuminance uniformity based on photometric measurements. The graph shows that "high" comfort sites tend to have relatively high illuminance uniformity. However a "low" comfort site and several "medium" comfort sites also have high illuminance uniformity suggesting that occupant satisfaction is based on more than just illuminance levels.

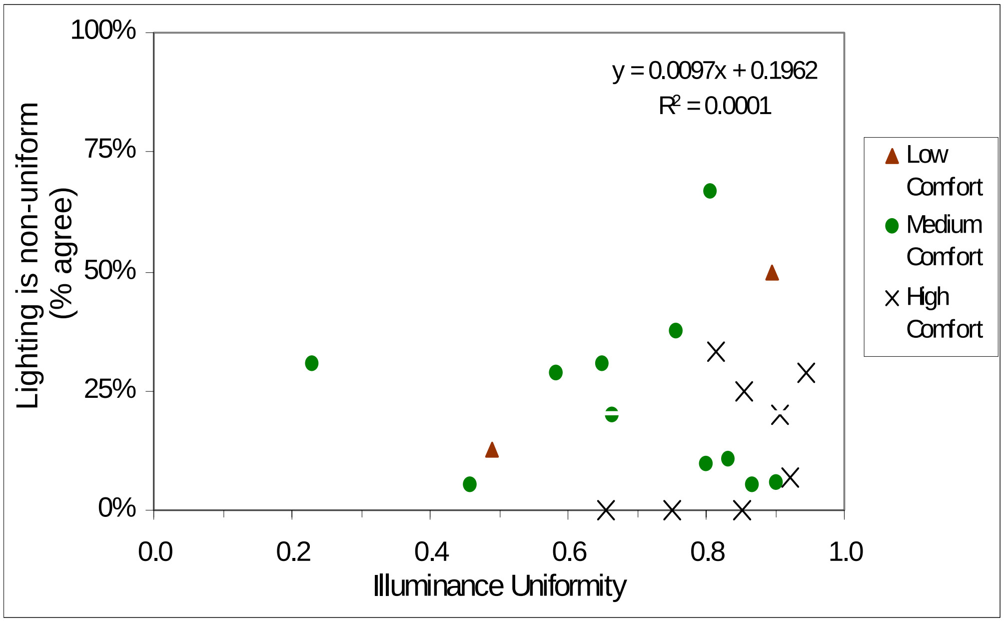

Figure 40. Classroom – Perception of Uniformity vs. Calculated Illuminance Uniformity

Figure 41 shows overall comfort compared to illuminance uniformity also indicating that there is no correlation between comfort and uniformity.

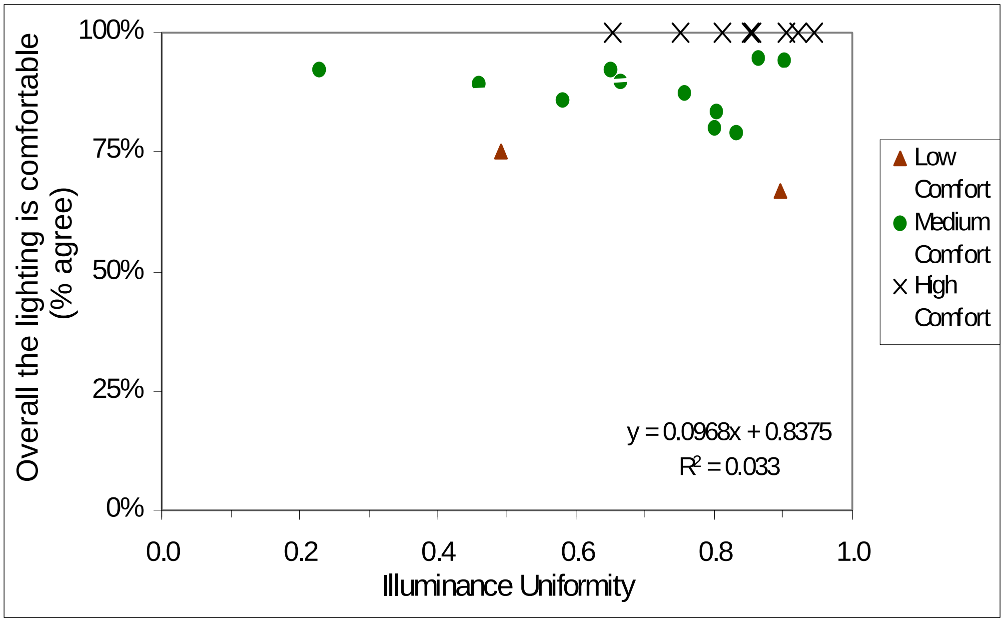

Figure 41. Classroom – Overall Comfort vs. Calculated Illuminance Uniformity

F.3 Site-Specific Findings

This section provides additional details for the "low" comfort sites, with comfort ratings less than 75%. Again, it should be noted that even these sites have average overall comfort ratings greater than the normative value of 69%.

F.3.1 Office Site-Specific Findings

The "low" comfort office sites presented in the previous sections are discussed below in order of LPD for ease of tracking (left to right on the graphs). Table 33 provides the values for both the comfort rating and LPD. It is interesting to note that the two sites with the lowest comfort rating also have the fewest number of respondents. For sites with very few respondents (less than 10) the response of one individual can have a significant impact on the overall results for the site.

Site No.	Comfort Rating	LPD	Number of Respondents
98C260	73%	0.80	11
96S27	71%	1.29	7
94P7387	73%	1.48	15
94P4875	73%	1.62	15
96S60	71%	1.64	7

Table 33. Office "Low Comfort" Comfort Ratings and LPD

98C260 – Overall comfort rating of 73%, uncomfortably bright (36% agree), not uncomfortably dim, and uniformity is a problem (55% agree). The measured illuminance uniformity is 0.43 indicating poor lighting uniformity in the space.

96S27 – Small office with seven respondents and an overall comfort rating of 71%. The lighting is not uncomfortably bright or uncomfortably dim. The results do not indicate why the lighting is not comfortable. This site had low satisfaction responses due more to apparent occupant indecision[14] and small sample size than to any particular problem with the lighting.

94P7387 – Site with several small offices with 15 respondents and an overall comfort rating of 73%. The lighting is not uncomfortably bright or uncomfortably dim, but is non-uniform. The measured illuminance uniformity is 0.49 indicating poor lighting uniformity in the space.

94P4875 – Overall comfort rating of 73%. The lighting is not uncomfortably bright or uncomfortably dim. The only other factor that appears to be an issue is "skin tones look unnatural under this light" (60% agree).

96S60 – Small office with seven respondents and an overall comfort rating of 71%. This site had low satisfaction responses due more to apparent occupant indecision[15] and small sample size than to any particular problem with the lighting.

F.3.2 Retail Site-Specific Findings

The two "low" comfort retail sites presented in the previous sections are discussed below in order of LPD for ease of tracking (left to right on the graphs).

94S0053 – Big box retailer with 11 respondents. Overall comfort ranking of 55% is the lowest of any of the retail sites. This site received the lowest ratings on all of the questions except for uncomfortably bright. Average horizontal illuminance is 64.8 fc and average vertical illuminance is 28.9 fc, both of which are about average. Measured illuminance uniformity is 0.84, which is good. The LPD is 1.83 W/sf, which is adequate for this type of space. There is no other information that describes specifically why the occupants are not comfortable. It should be noted that there were several big box retail sites in our sample and this was the only one with unsatisfactory results.

96S2778 – Retail space with seven respondents and an overall comfort rating of 71%. The LPD is 1.26 W/sf, which is slightly low for a retail space. Horizontal illuminance is 51.4 fc, which is below average. Vertical illuminance is 46.1 fc, which is above average. The lighting is not uncomfortably bright or uncomfortably dim. The percent agreement that the lighting is non-uniform is 57%. The measured illuminance uniformity is 0.64, which is adequate but not exceptional.

Lighting uniformity as perceived by the occupants, as discussed in the previous section, appears to be slightly correlated to occupant comfort. However, the occupants' perception of uniformity and the measured uniformity are not always correlated. Table 34 provides a list of the sites that were perceived by the

[14] On question #1 instead of circling the answer, one respondent underlined the N and put a question mark next to it.

[15] One respondent said both Y/N to the overall comfort question (Q1).

occupants to have non-uniform lighting. The table provides the values for the uniformity rating, LPD and measured uniformity, in order of LPD for ease of tracking (left to right on the previous graphs). A high non-uniformity rating means the respondents think the lighting is non-uniform.

Site No.	Non-Uniformity Rating	LPD	Number of Respondents
96P7	100%	0.99	1
94S0069	60%	1.05	5
96S57	55%	1.20	11
96S2278	57%	1.26	7
94S0053	82%	1.83	11
96S1175	90%	2.63	10

Table 34. Retail “Non-Uniformity” Ratings LPD and Calculated Illuminance Uniformity

The two “low comfort” sites (96S2278and 94S0053) were discussed above. The other sites are discussed below.

96P7 – Small retail space with one respondent and non-uniform lighting, but everything else is satisfactory.

94S0069 – High comfort site with five respondents. 60% of the respondents agree that the lighting is non-uniform, however the lighting uniformity based on photometric measurements is 0.84 indicating good uniformity. However, over 25% of the wattage came from incandescent spot lights, which could cause bright spots throughout the store.

96S57 – Medium comfort site with 11 respondents with non-uniform lighting according to the occupants. The lighting uniformity based on photometric measurements is 0.58, which is fairly low. Results from the other questions indicate general satisfaction with the lighting.

96S1175 – Medium comfort site with 10 respondents. 90% of the respondents indicated that uniformity is a problem. The lighting uniformity based on photometric measurements is 0.54, which is fairly low. Results from the other questions indicate general satisfaction with the lighting. The lighting system consisted of 90W halogen and 100W HPS spot lamps which tended to cause bright spots throughout the space, as opposed to uniform distribution.

F.3.3 Classroom Site-Specific Results

The two “low” comfort classroom sites presented in the previous sections were reviewed in detail to determine the cause of the low rating. They are discussed below.

96S72 – Elementary school with 16 respondents. Overall comfort rating is 75%. The classrooms were neither uncomfortably bright nor uncomfortably dim.

However the teachers registered displeasure with reflections on the boards and flickering and humming of the lights.

96P1364 - Children's center with six respondents. Overall comfort rating is 67%, uncomfortably bright rating is 33%. and lighting uniformity rating is 50%. The small sample size of respondents tends to skew the responses. Two of the six respondents said it was not comfortable, it was too bright and the lighting was non-uniform.

APPENDIX G. SAMPLING DESIGN

Southern California Edison Company
Nonresidential New Construction
Followup Baseline Study

Sample Design for the Lighting Validation
and Quality Assessment Study

February 28, 2000
RLW Analytics

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INTRODUCTION

This memo describes the sample design for the followup lighting study. The study has two principle objectives:

1. To assess any bias in the measurement of LPD in the original baseline study, and
2. To evaluation the quality of the lighting, especially in the sites with low LPD.

These two objectives are to be addressed by doing followup onsite work in a sample of about 75 of the baseline sites. To address both objectives, the sample should represent sites with low, medium, and high LPD but be matched as closely as possible on other characteristics, especially building type and size.

Once the sample of *sites* has been selected, a sample of *spaces* will be selected from each sample site. The spaces to be audited will be selected from the dominant space type of each building type. Specifically, office spaces will be selected from office buildings, retail spaces will be selected from retail buildings, and classrooms will be selected from schools.

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

Building Type	Sites
Office	231
Retail	162
School	169
Total	562

Table 1: Number of Available Sites by Building Type

CLEANING THE FRAME

The first step in developing the sample design was to eliminate sites that would be potential problems in the field. We first looked at the proportion of the total square footage of each site classified as the primary space type. The primary space type was considered to be office space for office buildings, retail space for retail buildings, and classroom space for schools. We only included sites if a high proportion of the total space was in the primary space type.

Secondly, we identified whether the original project that was audited was a new building or an addition or expansion to an existing building. We chose to focus on the new buildings in order to reduce the possibility of error in identifying the space that was originally audited and modeled.

Table 2 shows the results. We have 125 offices that are new and passed the primary space criterion. Similarly we have 128 retail and 84 schools. The remainder of the work will be with these 337 sites.

Count of Sites		Inclusion, Primary Space		
Building	New?	Yes	No	Total
Office	Yes	125	22	147
	No	62	22	84
Office Total		187	44	231
Retail	Yes	128	17	145
	No	12	5	17
Retail Total		140	22	162
School	Yes	84	15	99
	No	59	11	70
School Total		143	26	169
Grand Total		470	92	562

Table 2: Available Sites by Exclusion Criteria

CONSTRUCTING STRATA

The next step was to develop a stratification approach.

We worked with the following variables:

kSF = building size in thousand square feet, and

LPD = lighting watts per square foot in the primary space.

We also considered:

Eff Rat = as-build energy use / baseline energy use.

Segmentation by Lighting Power Density

We want to segment the sample to obtain a balanced sample of buildings with low LPD, medium LPD and. high LPD. To get started we created the scatterplots of LPD versus efficiency Ratio shown in Figures 1-3.

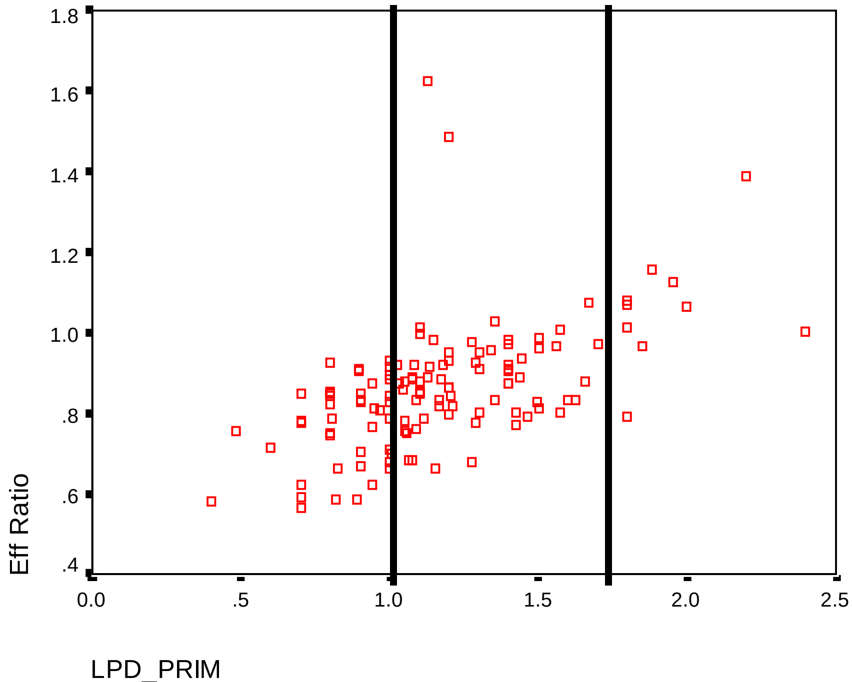

Figure 1: Scatterplot of LPD vs. Efficiency Ratio, Office Segment

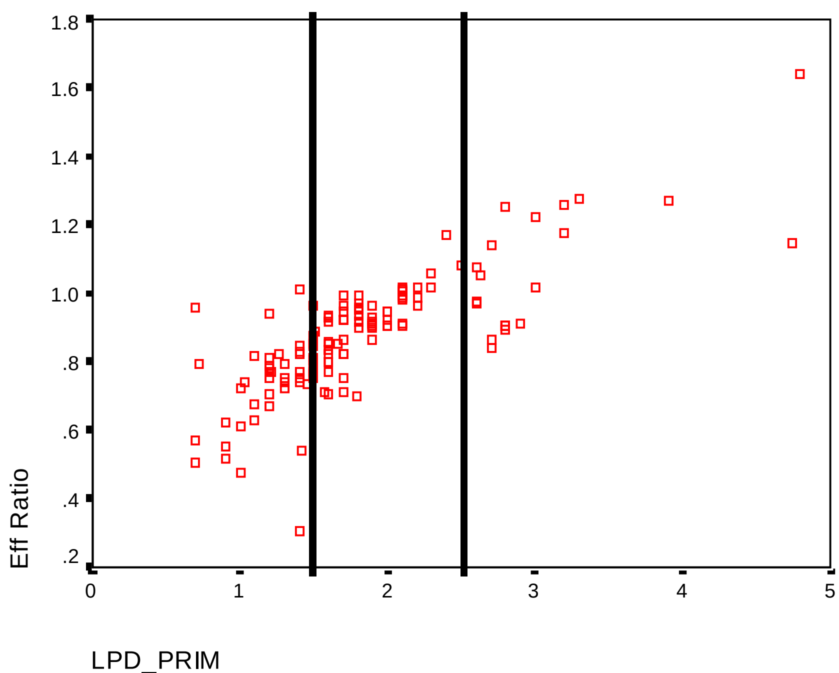

Figure 2: Scatterplot of LPD vs. Efficiency Ratio, Retail Segment

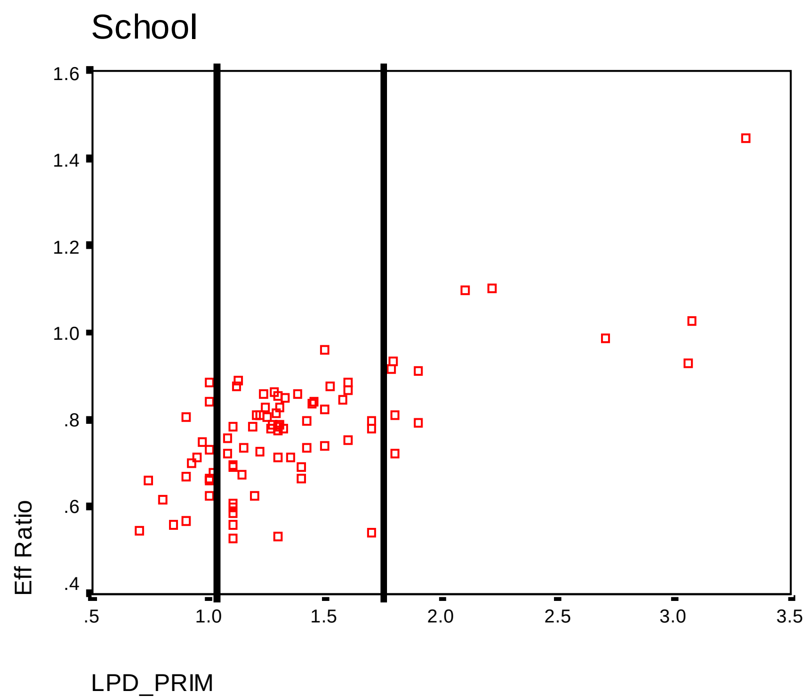

Figure 3: Scatterplot of LPD vs. Efficiency Ratio, School Segment

These graphs show that, except for a few outliers,[1] there is a fairly strong positive correlation between the whole-building efficiency ratio and the LDP of the primary space. In other words, buildings with lower LPD tend to be more efficient.

Our primary use of these scatterplots is to select the boundaries for defining low LPD, medium LPD and high LPD groups of sites. Based on these graphs we have selected the cutpoints shown in Table 3. For example, in the office category, a site will be considered to have low LPD if the LPD of the site is less than 1 watt per square foot, and high if the LPD is greater than 1.75 watt per square foot.

	LPD	
Building Type	Low	High
Office	1	1.75
Retail	1.5	2.5
School	1	1.75

Table 3: LPD Cutpoints

The following table shows the count of projects by LPD category. This shows that there is a good distribution of sites in each of the groups that we have defined.

[1] The two office sites with high Eff Ratio did not fall into the final sample.

Type	Low	Medium	High	Total
Office	39	77	9	125
Retail	50	60	18	128
School	13	61	10	84
Total	102	198	37	337

Table 4: Number of Sites by LPD Category

SEGMENTATION BY SIZE

Within each of these three building types, we want to match the sample buildings by secondary characteristics. For example in the school category, we would like to have a similar distribution of elementary, middle, and high schools in the three LDP categories. But unfortunately, we do not have information about the type of school building readily available for all 84 schools. Therefore it is not convenient to stratify the sample by this type of secondary characteristic.

Instead, we propose to stratify the sampling frame by size, i.e., square footage. We have defines size categories based on 50 kSF and 150 kSF in each of the three building types. Once we define suitable size strata, we will select the sample and a prioritized list of backup sites.

Office Sample Design

Figure 4 shows the relationship between size in 1,000 square feet and the LPD of the primary space for the office segment. The figure shows that there are three very large offices greater than 300 kSF. All have LPD near 1. While it might be interesting to learn whether the LPD measurements are accurate in these sites, there is little to be learned about the relationship between the quality of lighting and the LPD. Therefore we suggest that these be excluded from the sample.

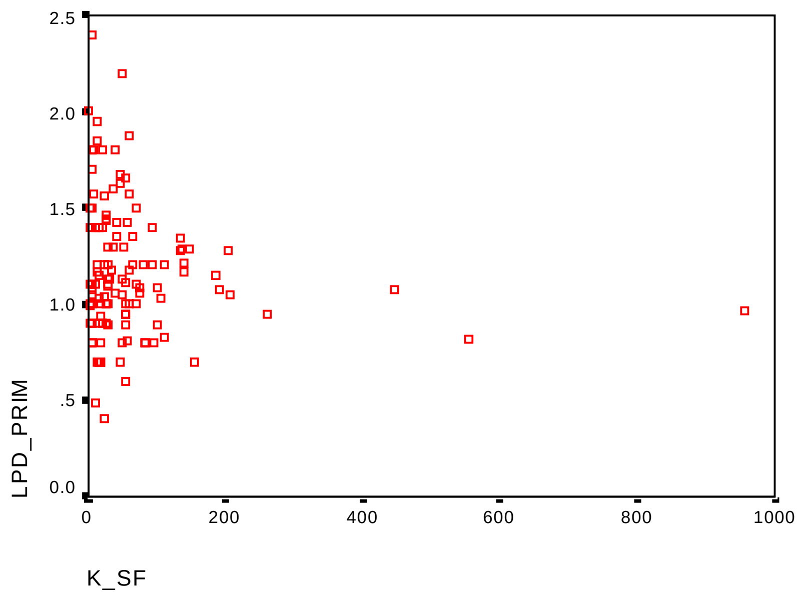

Figure 4: Scatterplot between LPD and k SQFT for Offices

Figure 5 shows the scatterplot of LPD and size for the remaining offices. Note that we have drawn in the boundaries for the proposed LPD and size categories. We have taken the LPD categories from Table 3. We have defines size categories based on 50 kSF and 150 kSF. Notice that almost all of the offices with high LPD (> 1.75) are less than 50 kSF. Thus if we want a meaningful comparison of offices with low, medium and high LPD, we should focus on offices less than 50 kSF.

However, there are a substantial number of buildings between 50 and 150 kSF. Among these buildings we will still be able to compare the sites with low LPD (less that 1 Watt per SF) and medium LPD.

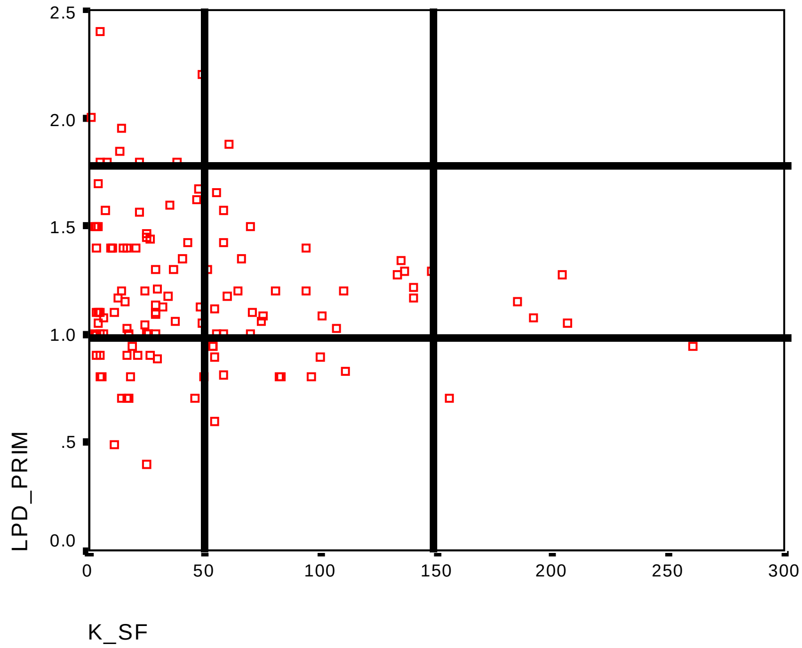

Figure 5: Scatterplot between LPD and k SQFT for Offices Less Than 300 kSF

Table 5 shows the number of sites in each of these size and LPD categories. For example in the small office category (< 50 kSF), there are a total of 78 sites. 19 of these have low LPD and 9 have high LPD. In the large office category, there are 9 sites, falling in the low and medium LPD categories. Recall that we have seen in Figure 5 that their LPD is actually very similar.

Size\LPD	Low	Medium	High	Total
Small	19	50	9	78
Medium	10	27	1	38
Large	4	5		9
Total	33	82	10	125

Table 5: Count of Sites by Size and LPD, Offices

Table 6 shows the proposed sample size in each of the strata shown in Table 5. We suggest allocating about one-third of the followup sites to the office category. The baseline sample itself was selected following an optimal sample design. Consequently, the followup sample should be allocated to each stratum in approximate proportion to the number of sites in the sample. Following these principles, we suggest the sample shown in Table 6

Size\LPD	Low	Medium	High	Total
Small	7	7	7	21
Medium	2	2	0	4
Large	0	0		0
Total	9	9	7	25

Table 6: Sample Sizes by Size and LPD, Offices

Retail Sample Design

Figure 6 shows the scatterplot for retail. In the case of retail, we have specified high LPD to be greater than 2.5 watts per sq ft. The figure shows that the majority of the sites with high LPD are smaller than 50 kSF. There are several sites greater than 150 kSF, almost all with low LPD.

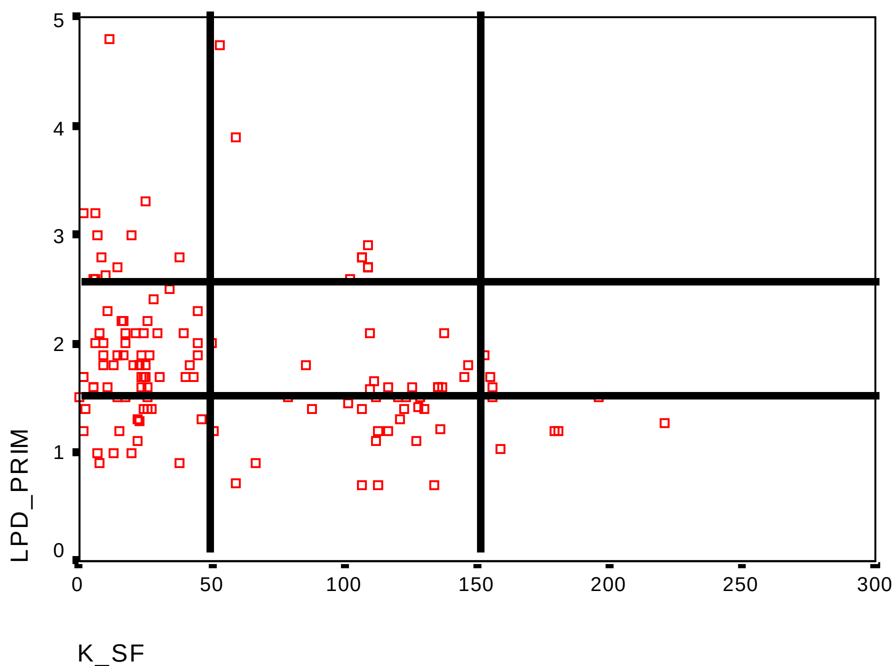

Figure 6: Scatterplot between LPD and k SQFT for Retail

Table 7 shows the number of sites in each of these size and LPD categories. For example, in the small retail category (< 50 kSF), there are a total of 74 sites. 15 of these have low LPD and 13 have high LPD. In the large retail category, 9 sites fall in the low and medium LPD categories.

Size\LPD	Low	Medium	High	Total
Small	15	46	13	74
Medium	18	18	9	45
Large	4	5		9
Total	37	69	22	128

Table 7: Count of Sites by Size and LPD, Retail

Table 8 shows the proposed sample size in each of the strata shown in Table 7. Since the LPD is somewhat more variable in the retail category, we suggest allocating slightly more than 1/3 of the sites to the retail category. We suggest the sample shown in Table 8. In the case of retail, we will compare the low, medium and high LPD categories for both small and medium sites.[2]

Size\LPD	Low	Medium	High	Total
Small	7	7	7	21
Medium	2	2	2	6
Large	0	0		0
Total	9	9	7	27

Table 8: Sample Sizes by Size and LPD, Retail

School Sample Design

Figure 7 shows this type of scatterplot for schools. Our cutpoints for LPD in the school category are 1 and 1.75 watts per SF. We propose to exclude the one school site greater than 150 kSF.

[2] In the spreadsheet, I have added two more sites to the retail sample, selected from the large retail category. We can either retain or drop these two sites without affecting the rest of the sample. If we choose to retain these sites, we can modify the report accordingly.

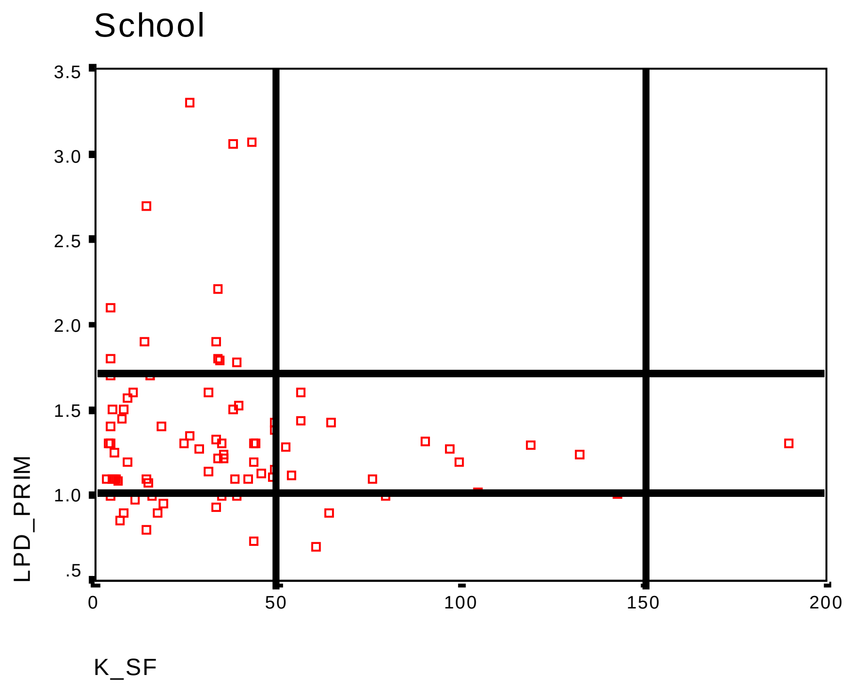

Figure 7: Scatterplot between LPD and k SQFT for Schools

Table 9 shows the number of sites in each of these size and LPD categories. For example, in the small school category (< 50 kSF), there are a total of 67 sites. 8 of these have low LPD and 12 have high LPD. In the medium school category, two sites fall in the low LPD category and 14 in the medium LPD category.

Size\LPD	Low	Medium	High	Total
Small	8	47	12	67
Medium	2	14		16
Large		1		1
Total	10	62	12	84

Table 9: Count of Sites by Size and LPD, Schools

We suggest the sample shown in Table 10. In the small schools we will seek to compare sites with low, medium and high LPD, and in the medium schools we will compare sites with low and medium LPD.

Size\LPD	Low	Medium	High	Total
Small	7	7	7	21
Medium	1	1		2
Large		0		1
Total	8	8	7	23

Table 10: Sample Sizes by Size and LPD, Schools

CHARACTERISTICS OF THE SAMPLE

In this section we will describe the initial samples according to other available characteristics:

- ✓ Year: 1994, 1996 or 1998
- ✓ Participant or nonparticipant
- ✓ Utility
- ✓ Ownership

Table 11 shows the number of sample sites by year. Results are given for each stratum. Among all 75 sites, 22 are from 1994, 32 from 1996, and 21 from 1998. In each of the Type and Size categories, the distribution among the three years is about the same for the three LPD categories. An exception is the small school category, in which the medium LPD category contains more 1998 sites than the other two categories. But in general it seems that the sample is sufficiently well balanced by year so that the results will not be distorted by any differences in the audit procedure from year to year.

Type	Size	LPD	1994	1996	1998	Total
Office	Small	Low	2	4	1	7
		Med		5	2	7
		High	3	3	1	7
	Medium	Low	1		1	2
		Med		1	1	2
Retail	Small	Low	1	3	3	7
		Med		4	3	7
		High	1	4	2	7
	Medium	Low	1		1	2
		Med	1	1		2
		High	1	1		2
School	Small	Low	5	2		7
		Med	1	2	4	7
		High	5	1	1	7
	Medium	Low		1		1
		Med			1	1
Total			22	32	21	75

Table 11: Sample Sites by Year

Table 12 shows the number of sample sites by the participation status. Overall, 49 of the 75 sample sites are non-participants. The number of non-participants relative to participants is higher in most of the strata, with the exception of small offices with medium LPD and small schools with low LPD. In general it seems that the sample is sufficiently well balanced by participation status.

Type	Size	LPD	Non-P	Part.	Total
Office	Small	Low	4	3	7
		Med	3	4	7
		High	6	1	7
	Medium	Low	1	1	2
		Med	1	1	2
Retail	Small	Low	4	3	7
		Med	5	2	7
		High	6	1	7
	Medium	Low	1	1	2
		Med		2	2
		High	1	1	2
School	Small	Low	3	4	7
		Med	6	1	7
		High	6	1	7
	Medium	Low	1		1
		Med	1		1
Total			49	26	75

Table 12: Sample Sites by Participation Status

Type	Size	LPD	PGE	SCE	SDGE	Total
Office	Small	Low	4	3		7
		Med	2	5		7
		High	4	2	1	7
	Medium	Low	2			2
		Med	1	1		2
Retail	Small	Low	3	4		7
		Med	3	4		7
		High	2	4	1	7
	Medium	Low		2		2
		Med	1	1		2
		High		2		2
School	Small	Low	6	1		7
		Med	6	1		7
		High	1	5	1	7
	Medium	Low		1		1
		Med	1			1
Total			36	36	3	75

Table 13: Sample Sites by Utility

Table 13 shows the number of sample sites by utility. As might be expected most of the sites are from PGE and SCE since most of the sites in the baseline study were from the PGE and SCE impact evaluations. This tends to be true in most of the strata, so the sample appears to be sufficiently well balanced by utility.

Table 14 shows the number of sample sites by the ownership status. Overall, 52 of the 75 sample sites are private. Of course, in the school category, the majority of the sites are public. In general it seems that the sample is sufficiently well balanced by ownership status within each stratum.

Type	Size	LPD	Private	Public	Total
Office	Small	Low	6	1	7
		Med	5	2	7
		High	6	1	7
	Medium	Low	2		2
		Med	2		2
Retail	Small	Low	7		7
		Med	7		7
		High	7		7
	Medium	Low	2		2
		Med	2		2
		High	2		2
School	Small	Low	1	6	7
		Med	2	5	7
		High	1	6	7
	Medium	Low		1	1
		Med		1	1
Total			52	23	75

Table 14: Sample Sites by Ownership

Table 15 shows the number of sample sites by owner occupied vs. speculative. Overall, 59 of the 75 sample sites are owner occupied. The owner-occupied sites outnumber the speculative sites in most of the strata. The exception is in the small offices with high LPD. Of course, in the school category, all of the sites are owner occupied. In general it seems that the sample is sufficiently well balanced by owner occupied vs. speculative status.

Type	Size	LPD	Own. Occ.	Spec	Total
Office	Small	Low	6	1	7
		Med	6	1	7
		High	2	5	7
	Medium	Low	2		2
		Med	1	1	2
Retail	Small	Low	5	2	7
		Med	6	1	7
		High	4	3	7
	Medium	Low	1	1	2
		Med	2		2
		High	1	1	2
School	Small	Low	7		7
		Med	7		7
		High	7		7
	Medium	Low	1		1
		Med	1		1
Total			59	16	75

Table 15: Sample Sites by Owner Occupied vs. Speculative