



Daylighting and Productivity - CEC PIER

Executive Summaries

- [Windows and Offices](#)
- [Windows and Classrooms](#)
- [Daylight and Retail Sales](#)
- [Daylighting in Schools - Additional Analysis](#)
- [Daylighting in Schools - PG&E 1999](#)
- [Skylighting and Retail Sales - PG&E 1999](#)

Windows and Offices: A Study of Office Worker Performance and the Indoor Environment – CEC PIER 2003

This study reports on an investigation into the influences indoor physical environment has on office worker performance. It is particularly concerned with the potential contributions of windows and daylight to improved performance by office workers. Two different studies were conducted at the same organization, the Sacramento Municipal Utility District. The first study looked at 100 workers in an incoming call center, whose performance was continuously tracked by a computer system and measured in terms of time to handle each call. The second study examined the performance of 200 other office workers on a series of short cognitive assessment tests, taken at each individual's desktop computer.

The study sites provided a range of daylight, view and ventilation conditions, while providing a relatively uniform environment for other potential influences on worker performance. All of the office work considered was computer-based, based on self-illuminated tasks. Extensive data was collected about the physical environment at each office worker's cubicle. Multivariate regression analysis was used to control for other potential influences, such as age or employment status. A variety of statistical models were tested to determine if any of the variations in environmental conditions, either between workers or during different time periods for a given worker, were significantly associated with differences in worker performance.

The studies found several physical conditions that were significantly associated ($p < 0.10$) with worker performance, when controlling for other influences. Having a better view out of a window, gauged primarily by the size of the view and secondarily by greater vegetation content, was most consistently associated with better worker performance in six out of eight outcomes considered. Workers in the Call Center were found to process calls 6% to 12% faster when they had the best possible view versus those with no view. Office workers were found to perform 10% to 25% better on tests of mental function and memory recall when they had the best possible view versus those with no view. Furthermore, office worker self reports of better health conditions were strongly associated with better views. Those workers in the Desktop study with the best views were the least likely to report negative health symptoms. Reports of increased fatigue were most strongly associated with a lack of view.

Other variables related to view were also found significant. In the Call Center higher cubicle partitions were associated with slower performance. In the Desktop study glare potential from windows was found to have a significant negative effect on performance in three of the five mental function assessment tests. In the three tests, the greater the glare potential from primary view windows, the worse the office worker performance, decreasing by 15% to 21%, all other things being equal.

Horizontal daylight illumination levels were found to have an inconsistent relationship to performance, significant in two out of eight metrics tested. Higher levels of daylight illumination were found positive for Digit Span Backwards, a test measuring attention span and short term memory, and negative when compared to changes in daily average speed of handling calls for one of two study periods. The natural log of daylight illumination levels was found to have the best mathematical fit to the data, implying more sensitivity to changes at lower levels of illumination and progressively less sensitivity at higher levels.

Ventilation status and air temperature were also found to have significant, if intertwined and occasionally contradictory, associations with worker performance. When variation in hourly performance at the Call Center was considered, higher rates of outside air delivery were significantly associated with faster handling of calls.

Overall these potential influences on worker performance were found to have high statistical significance in the models tested. They are related to performance that is 1% to 20% better or worse than average. All together information about the physical conditions of the workers was able to explain about 2% to 5% of the total variation observed in a measure of worker productivity (Call Center study) or in performance on short cognitive assessment tests that were thought to be related to worker productivity (Desktop study).

Even small improvements in worker productivity are of great practical importance, and explaining 2%-5% of total variation is not trivial. By way of comparison, all other available information typically believed to predict performance such as demographic characteristics or employment status was able to explain about 6% to 19% of the variation in their performance. Thus the characteristics of the physical environment represent about 1/8th to 1/3rd of our entire ability to predict variation in individual worker performance.

Furthermore, changes in the physical design of a space that may influence worker performance are likely to have great persistence, continuing for the life of the building. When compared with the costs, persistence and the certainty of other methods of increasing productivity, constructing well-designed buildings may be attractively cost-effective. As demonstrated in the study site, these same features can also provide additional energy cost savings.

Both studies successfully measured variation in office worker environmental conditions and related these to measured office worker performance under actual employment conditions. The Desktop study pioneered the use of computerized cognitive assessment tools to gauge office worker performance in field conditions. The studies have shown that indoor environmental conditions can have a measurable relationship to changes in office worker performance and have established a range of likely effect sizes that other researchers can use to refine the needs of future studies. Other studies will be required to test if these findings can be replicated in other settings and to explore potential causal mechanisms between the environmental conditions and worker performance.

Windows and Classrooms: A Study of Student Performance and the Indoor Environment – CEC PIER 2003

This study investigates whether daylight and other aspects of the indoor environment in elementary school student classrooms have an effect on student learning, as measured by their improvement on standardized math and reading tests over an academic year. The study uses regression analysis to compare the performance of over 8000 3rd through 6th grade students in 450 classrooms in the Fresno Unified School District, located in California's Central Valley. Statistical models were used to examine the relationship between elementary students' test improvement and the presence of daylight in their classrooms, while controlling for traditional education explanatory variables, such as student and teacher demographic characteristics. Numerous other physical attributes of the classroom were also investigated as potential influences, including ventilation, indoor air quality, thermal comfort,

acoustics, electric lighting, quality of view out of windows, and the type of classroom, such as open or traditional plan, or portable classroom.

Previous Studies

This study is the third in a series of studies looking at the relationship between daylighting and student performance. The first, *Daylighting in Schools*,^[1] which was completed for Pacific Gas and Electric in 1999, examined school districts in three states. In Seattle Washington and Fort Collins Colorado, where end-of-year test scores were used as the outcome variable, students in classrooms with the most daylighting were found to have 7% to 18% higher scores than those with the least. In San Juan Capistrano, California, where the study was able to examine the improvement between fall and spring test scores, we found that students with the most daylighting in their classrooms progressed 20% faster on math tests and 26% faster on reading tests in one year than in those with the least.

A second study, the *Daylighting in Schools Reanalysis Report*^[2] completed for the California Energy Commission in 2001 further investigated the results from the Capistrano school district. We investigated whether better teachers were being stationed in more daylit classrooms, and thereby inflating the importance of the daylight variable. In that district, we found that there was no assignment bias of better teachers to more daylit classrooms. Furthermore, the addition of information about teacher characteristics to the original student performance models did not reduce the significance or magnitude of the daylight variables. Among twelve models considered in that study we identified a central tendency of a 21% improvement in student learning rates from those in classrooms with the least amount of daylight compared to those with the most.

Fresno Study

This study's primary goal was to examine another school district, one with a different climate and curricula, to see whether the original methodology and findings would hold. We collected more information about the lighting and daylighting conditions in the classrooms, to allow us to test which attributes of a daylit classroom were more likely to contribute to a "daylight effect," if any. We also wished to understand how other aspects of the indoor environment affected student performance and interacted with daylight. To accomplish these goals, this study gathered detailed information about classroom conditions, including lighting and daylighting, HVAC, ventilation, windows, surface coverings, view, and indoor air quality. Whereas we had done on-site surveys only a sample of classrooms for the previous studies, for this study we went on-site to measure attributes in every classroom, surveying a total of 500 classrooms in 36 schools.

The preliminary statistical analyses replicated the structure of the models used in the previous studies. They used a holistic variable called the Daylight Code to rate classrooms by the amount of daylight available throughout the school year. In these replication models, the Daylight Code was not significant in predicting student performance for Fresno. It had the least explanatory power of the variables considered, and lowest significance level. Thus, we could not replicate the Capistrano findings based on a similar model structure. We proceeded with more detailed statistical analysis to see if we could identify specific influences of school or classroom design on student performance, and perhaps gain some insight as to why the Daylight Code was not significant in Fresno as it had been in Capistrano, Seattle and Fort Collins.

We used multi-linear regression analysis to test a wide variety of variables to see which provided the best explanation of student performance. Of the variables describing the physical conditions of classrooms and schools, characteristics describing windows were generally quite stable in their association with better or worse student performance. Variables describing a better view out of windows always entered the equations as positive and highly significant, while variables describing, glare, sun penetration and lack of visual control always entered the models as negative.

In addition, attributes of classrooms associated with acoustic conditions and air quality issues followed a similar pattern. Those variables representing sources of internal noise, such as a loud HVAC system or a loud ballast hum from the lighting system, were consistently associated with negative student performance, while increasing the amount of carpet (which reduces acoustic reverberance) in the classroom was associated with better student performance in reading. Variables related to indoor air quality showed that in Fresno automatically controlled mechanical ventilation (No Teacher Control of Fan) was positive, while visible water damage or a surveyor assessment of musty air in the classroom was negative.

Summary of Study Findings

The findings of regression models in this study support the general conclusions that:

- The visual environment is very important for learning.
- An ample and pleasant view out of a window, that includes vegetation or human activity and objects in the far distance, supports better outcomes of student learning.
- Sources of glare negatively impact student learning. This is especially true for math learning, where instruction is often visually demonstrated on the front teaching wall. Per our observations, when teachers have white marker boards, rather than black or green chalk boards, they are more likely to use them and children perform better in math.
- Direct sun penetration into classrooms, especially through unshaded east or south facing windows, is associated with negative student performance, likely causing both glare and thermal discomfort.
- Blinds or curtains allow teachers to control the intermittent sources of glare or visual distraction through their windows. When teachers do not have control of their windows, student performance is negatively affected.
- The acoustic environment is also very important for learning. Situations that compromise student focus on the lessons at hand, such as reverberant spaces; annoying equipment sounds, or excessive noise from outside the classroom, have measurable negative effects on learning rates.
- Poor ventilation and indoor air quality also appear to negatively affect student performance. However, in FUSD these issues are almost hopelessly intertwined with thermal comfort, outdoor air quality and acoustic conditions. Teachers often must choose to improve one while making another aspect of the classroom worse.
- Physical characteristics of classrooms are just as likely to affect student learning as many other factors commonly given much more public policy attention. Variables describing the physical conditions of classrooms, most notably the window characteristics, were as significant and of equal or greater magnitude as teacher characteristics, number of computers, or attendance rates in predicting student performance.

Problems with Daylit Classrooms

We tested each statistical model with and without the Daylight Code. When we added the Daylight Code the other variables remained essentially the same, but the Daylight Code always came in as significant and negative, telling us that there was some characteristic of classrooms sorted by the Daylight Code that was associated with a negative effect. Examination of the performance of individual classrooms, considering all of their window characteristics plus the Daylight Code, showed that there were three types of classrooms in Fresno that were performing particularly well in relationship to their daylight characteristics—finger plan classrooms, grouped plan classrooms and portables—as long as they had no glare or other undesirable window characteristics. Thus,

classrooms with both the highest and the lowest Daylight Code were seen to support better student performance.

Many potential explanations for the negative influence of the Daylight Code were considered, and we went back on site to see if there were any systematic reasons why students in classrooms with a higher Daylight Code would perform worse, or those in classrooms with a low Daylight Code would perform better. In this second phase of the study, detailed examination of a number of potential confounding variables, including view-related distractions, glare, operable windows, radiant thermal comfort, indoor air quality and acoustic performance were considered. To better understand the results of the regression analysis, we visited 40 classrooms while they were in operation and surveyed 116 teachers about their assessment of and operation of their classrooms.

Overall, the daylit classrooms in Fresno had some consistent problems that might have degraded student performance, and which we believe did not exist in the previous districts studied. The most compelling of these were the acoustic problems created in the daylit classrooms. We found the classrooms with high daylight codes to have reverberation levels above current national recommendations, while classrooms with low daylight codes typically met or exceeded those recommendations. This reverberation problem tended to be aggravated by the presence of teaching assistants who provide in-class tutorials for individuals or small groups. In low Daylight Code classrooms these tutorials were often held outside of the classroom in conveniently adjacent common areas, while in the high Daylight Code classrooms they took place in the back of the classroom, raising the background noise level and making the teacher's voice less intelligible.

In addition, we noted teachers in classrooms with a high Daylight Code were more likely to teach with their windows open, primarily to compensate for poor temperature control and to improve ventilation. These open windows allowed in more noise from the outside, exacerbated by crowded schools running on multiple lunch and recess schedules. We noted from the various regression models that, on the one hand, continuous mechanical ventilation seemed to improve student performance, while on the other hand, a higher percentage of operable windows were associated with lowered performance. We hypothesize that the poor outdoor air quality in Fresno [3], combined with the epidemic of asthma in school children, suggests the preferred use of mechanically filtered air rather than natural ventilation in FUSD.

We also considered whether the problems we detected with daylit classrooms could be rectified, and calculated the value of potential energy savings if daylit classrooms were operated to reduce reliance on electric lighting. Acoustic analysis of the daylit classrooms showed that the reverberance problem could be corrected with the use of more sound-absorbing surfaces, such as carpet and high quality acoustic tile. The use of dual pane low-e glazing on the windows could simultaneously improve both the acoustic conditions in the classrooms and thermal comfort. Energy analysis showed substantial potential savings (1.1 kwh/sf) for retrofitting existing FUSD daylit classrooms with photocontrols. California could achieve an additional 3300 to 4800 megawatthours (0.6 to 0.9 kwh/sf) of energy savings statewide for each year that all new school construction included good daylighting design with photocontrols. This would accumulate to 33,000 to 48,000 megawatthours per year savings after ten years.

The Importance of School Design Choices

These findings suggest the importance school planners should give to the architectural design of schools. The statistical models repeatedly demonstrate that physical condition of classrooms and schools are just as likely to affect student learning as many other factors commonly given much more public policy attention. Variables describing the physical conditions of classrooms, most notably the window characteristics, were as significant and of equal or greater magnitude as teacher characteristics, number of computers, or attendance rates in predicting student performance. The partial R² of the different variable types is also very informative. The one variable which is specific to the individual—their fall test score—predicts about 10% of the variation in the gain from fall to spring. The demographic variables, which describe generic groups to which the individual belongs, predict

performance with an order of magnitude less precise, or about 1% each. The physical characteristics of the schools again drop another order of magnitude in predictive power, each significant variable describing on the order of 0.1% of the variation in student performance.

However, even though the physical characteristics of classroom have a very minor potential influence on the performance of a given individual, they will reliably affect hundreds or thousands of students over the life of the building, typically 50 years. Since the design of classrooms is entirely within the control of the school district, much more so than student or teacher demographics, optimized design of schools should be a central concern for all new school construction.

Daylight and Retail Sales – CEC PIER 2003

This study presents evidence that a major retailer is experiencing higher sales in daylit stores than in similar non-daylit stores. Statistical models were used to examine the relationship between average monthly sales levels and the presence of daylight in the stores, while simultaneously controlling for more traditional explanatory variables such as size and age of the store, amount of parking, local neighborhood demographics, number of competitors, and other store characteristics. The retailer, who will remain anonymous, allowed us to study 73 store locations in California from 1999 to 2001. Of these, 24 stores had a significant amount of daylight illumination, provided primarily by diffusing skylights.

This study was performed as a follow-on to a similar study completed for Pacific Gas and Electric in 1999^[4], which found that for a certain retail chain, all other things being equal, stores with skylights experienced 40% higher sales than those without skylights. This study, on behalf of the California Energy Commission, examined a second retail chain, in an entirely different retail sector, to see if the original findings would hold in a new situation, and if we could learn more about any daylight effect that might exist.

As a first step in this process, a simple model with daylight as a yes/no variable, and using basically the same format and inputs as the previous study, did not find a significant correlation between the presence of daylight, and increased sales. We then pursued the study in greater detail, adding more information to the model and describing daylight on a continuous scale by the number of daylit hours per year in each store.

The retailer in this study had a less aggressive daylighting design strategy and also more variation in both the range of daylight conditions and the range of store designs than the retailer in the first study. For this study, we collected much more detailed information about the characteristics of each store, and verified all information on site. Neighborhood demographics and retail competition were described using detailed, site-specific GIS analysis. Store managers were interviewed and employees were surveyed about their observations and preferences. For the final analysis, the amount of daylight in each store was described as the number of hours per year that daylight illumination levels exceeded the design electric illumination level.

Statistical regression models of average sales for the stores, using up to 50 explanatory variables, and both linear and natural log descriptions of the variables, found that increased hours of daylight per store were strongly associated with increased sales, but at a much smaller magnitude than the previous study. In addition, for this chain, the daylight effect on sales was found to be constrained by the amount of parking available at the store site. Sites with parking lots smaller than the norm experienced decreased sales associated with daylight, while stores with average and ample parking experienced increased sales as both the amount of daylight and parking increased. The statistical models were also more comprehensive, explaining about 75% of the variation in the data (model $R^2=0.75$), compared to 58% in the previous study.

Specifically, this study found that:

- Average effect of daylighting on sales for all daylit stores in this chain was variously calculated from 0% to 6%, depending on the type of model and time period considered.
- A dose/response relationship was found, whereby more hours of useful daylight per year in a store are associated with a greater daylight effect on sales.
- No seasonal patterns to this daylight effect were observed.
- A bound of an empirical daylight effect for this chain was detailed, with a maximum effect found in the most favorable stores of about a 40% increase in sales. This upper bound is consistent with our previous finding.
- Daylight was found to have as much explanatory power in predicting sales (as indicated by the variable's partial R²) as other more traditional measures of retail potential, such as parking area, number of local competitors, and neighborhood demographics.
- Along with an increase in average monthly sales, the daylit stores were also found to have slightly smaller increase in the number of transactions per month.
- The retailer reported that the primary motivation for the inclusion of daylight was to save on energy costs by having photocontrols turn off electric lights when sufficient daylight was detected. The retailer has been very pleased with the resulting reduction in operating costs. Based on current energy prices we estimated average whole building energy savings for the daylit stores at \$0.24/sf for the current design, with a potential for up to \$0.66/sf with a state-of-the art design.
- The value of the energy savings from the daylighting is far overshadowed by the value of the predicted increase in sales due to daylighting. By the most conservative estimate, the profit from increased sales associated with daylight is worth at least 19 times more than the energy savings, and more likely, may be worth 45-100 times more than the energy savings.
- During the California power crisis of 2001, when almost all retailers in the state were operating their stores at half lighting power, the stores in this chain with daylight were found to benefit the most, with an average 5.5% increase in sales relative to the other non-daylit stores within the chain (even while all stores in this chain increased their sales compared to the previous period).
- Employees of the daylit stores reported slightly higher satisfaction with the lighting quality conditions overall than those in the non-daylit stores. Most strikingly, they perceived the daylit stores to have more uniform lighting than the non-daylit stores, even though direct measurements showed both horizontal and vertical illuminance levels in the daylight stores to be substantially less uniform.
- Store managers did not report any increase in maintenance attributable to the skylights.
- The chain studied was found to be saving about \$0.24/sf per year (2003 energy prices) due to use of photocontrols, which could potentially increase up to \$0.66/sf per year with an optimized daylighting system.

Re-Analysis Report: Daylighting in Schools, Additional Analysis – CEC PIER 2001

This report is a follow-on study to the Daylighting in Schools study^[5] that was completed in 1999, which found a compelling statistical correlation between the amount of daylighting in elementary school classrooms and the performance of students on standardized math and reading tests. This re-analysis of the original study data was intended to answer key questions raised by the peer review of the earlier study, and expand our understanding of methodological choices for further work.

The original findings potentially have very important implications for the design of schools and other buildings where people live, work and play. Daylight used to be common, and even required in schools, homes and offices, but fully daylit buildings became increasingly rare as electric lighting became more the norm. This re-analysis study helps to provide greater certainty for the original findings.

For this re-analysis study HMG conducted four tasks:

- The Teacher Survey collected information from a sample of teachers in the Capistrano school district about their education and experience levels, preferences for classroom features and operation of those features. The primary purpose of the survey was to provide input to a subsequent "assignment bias" analysis. In addition, we learned some useful information about teacher preferences, attitudes and behaviors in response to classrooms conditions.
- While the teachers we surveyed generally had a preference for windows, daylight and views in their classrooms, these preferences were not found to be driving classroom preferences. Far more important was an almost universal desire for more space, a good location, quiet, lots of storage and water in the classroom.
- Environmental control was also found to be an important issue for teachers, especially for those who did not have full control. Teachers seemed to hold a basic expectation that they would be able to control light levels, sun penetration, acoustic conditions, temperature and ventilation in their classrooms. They made passionate comments about the need for improvement if one or more of these environmental conditions could not be controlled in their classroom.
- The Teacher Bias Analysis further examined information from the Teacher Survey. The survey data was coded into variables and statistically analyzed in relation to both assignment to daylit classrooms and the student performance models. The goal of the Bias Analysis was to discover if the original study had over-inflated the effect of daylight on student learning by not accounting for a potential "assignment bias" of better teachers to more daylit classrooms.

We conclusively found that there was not an "assignment bias" influencing our results. None of the individual teacher characteristics we identified were significant in explaining assignment to a daylit classroom in the Capistrano District. Considering all teacher characteristics together only explained 1% of the variation in assignment to daylit classrooms. We did find that a few types of teachers, those with more experience or honors, were slightly more likely (1%-5%) to be assigned to classrooms with more windows or some types of skylights.

When we added the teacher characteristics to the original student performance models, the daylight variables were not reduced in significance. Further analysis of other sub-populations repeated these findings. Among twelve models considered, we identified a central tendency of a 21% improvement in student learning rates from those in classrooms with the least amount of daylight compared to those with the most.

In the Grade Level Analysis, we re-analyzed the original student test score data for both Capistrano and Seattle by separate grade level, instead of aggregating the data across the four grade levels (2-5). Our goal was to determine if this method would more accurately explain the relationship of student performance to daylighting. We tested for statistical significance and correlation, and we looked at any patterns discovered in the analysis.

The data did not show any significant patterns between a daylight effect and the separate grade levels, neither an increase or decrease in daylight effects by grade level. Thus, we conclude that there do not seem to be progressive effects as children get older, nor do younger children seem to be more sensitive to daylight than older children. Allowing the results to vary by grade did not noticeably

improve the accuracy of the models. Therefore, we conclude that looking at data across grade levels is a sufficiently accurate methodology.

In the Absenteeism Analysis, we used absenteeism and tardiness data in the original Capistrano data set as dependent variables and evaluated them against the full set of explanatory variables from the original study, plus the new information on teacher characteristics. These models would allow us to assess whether daylighting or other classroom physical attributes potentially impacted student health, as measured by changes in student attendance.

Student attendance data is certainly not the best indicator of student health. Yet to the extent that attendance data does reflect student health, our findings do not suggest an obvious connection between physical classroom characteristics and student health. Notably, daylighting conditions, operable windows, air conditioning and portable classrooms were not found to be significant in predicting student absences.

Overall, the strength of the daylight variable in predicting student performance stands out sharply across all of these re-analysis efforts.

This analysis also demonstrated that the findings of these models are more strongly dependent upon the sample population than the subtleties of the explanatory variables. Thus, we believe that it will be more informative to replicate this study with a different population, to continue to try to refine the models with further detail in the explanatory variables.

Daylighting in Schools – PG&E 1999

An Investigation into the Relationship between Daylighting and Human Performance

This study looks at the effect of daylighting on human performance. It includes a focus on skylighting as a way to isolate daylight as an illumination source, and separate illumination effects from other qualities associated with daylighting from windows. In this project, we established a statistically compelling connection between daylighting and student performance, and between skylighting and retail sales. This report focuses on the school analysis.

We obtained student performance data from three elementary school districts and looked for a correlation to the amount of daylight provided by each student's classroom environment. We used data from second through fifth grade students in elementary schools because there is extensive data available from highly standardized tests administered to these students, and because elementary school students are generally assigned to one teacher in one classroom for the school year. Thus, we reasoned that if the physical environment does indeed have an effect on student performance, we would be mostly likely to be able to establish such a correlation by looking at the performance of elementary school students.

We analyzed test score results for over 21,000 student records from the three districts, located in Orange County, California, Seattle, Washington, and Fort Collins, Colorado. The data sets included information about student demographic characteristics and participation in special school programs. We reviewed architectural plans, aerial photographs and maintenance records and visited a sample of the schools in each district to classify the daylighting conditions in over 2000 classrooms. Each classroom was assigned a series of codes on a simple 0-5 scale indicating the size and tint of its windows, the presence and type of any skylighting, and the overall amount of daylight expected.

The study used multivariate linear regression analysis to control for other influences on student performance. Regressions were compared using data from two separate tests, math and reading, for each district. Each math and reading model was also run separately using first the window and skylight codes, and then the overall daylight code. We reasoned that if daylight effects were truly robust the variables should perform similarly in all models. Thus, we created a total of twelve models

for comparison, consisting of four models for each of three districts.

The daylighting conditions at the Capistrano school district were the most diverse, and the data from that district were also the most detailed. Thus Capistrano became our most precise model. In this district, we were able to study the change in student test scores over a school year. Controlling for all other influences, we found that students with the most daylighting in their classrooms progressed 20% faster on math tests and 26% on reading tests in one year than those with the least. Similarly, students with the largest window areas were found to progress 15% faster in math and 23% faster in reading than those with the least. And students that had a well-designed skylight in their room, one that diffused the daylight throughout the room and which allowed teachers to control the amount of daylight entering the room, also improved by 19-20% faster than those students without a skylight. We also identified another window-related effect, in that students in classrooms where windows could be opened were found to progress 7-8% faster than those with fixed windows, regardless of whether they also had air conditioning. These effects were all observed with 99% statistical certainty.

The studies in Seattle and Fort Collins used the final scores on math and reading tests at the end of the school year, rather than the amount of change from the beginning of the year. In both of these districts we also found positive, and highly significant, effects for daylighting. Students in classrooms with the most daylighting were found to have 7% to 18% higher scores than those with the least.

The three districts have different curriculum and teaching styles, different school building designs and very different climates. And yet the results of studies show consistently positive and highly significant effects. This consistency persuasively argues that there is a valid and predictable effect of daylighting on student performance.

The results of this study of student performance, when combined with the companion study showing the positive effect of skylighting on retail sales, also strongly support the thesis that these performance benefits from daylighting can be translated to other building types and human activities.

Skylighting and Retail Sales – PG&E 1999

An Investigation into the Relationship between Daylighting and Human Performance

This study looks at the effect of daylighting on human performance. It specifically focuses on skylighting as a way to isolate daylight as an illumination source, and avoid all of the other qualities associated with daylighting from windows. In this project, we established a statistically compelling connection between skylighting and retail sales, and between daylighting and student performance. This report focuses on the retail analysis.

We analyzed data on the sales performance of a chain retailer who operates a set of nearly identical stores. The analysis included 108 stores, where two thirds of the stores have skylighting and one third do not. The design and operation of all the store sites is remarkably uniform, with the exception of the presence of skylights in some. The electric lighting was primarily fluorescent. The skylights often provided far more illumination, often two to three times the target illumination levels. Photo-sensor controls turned off some of the fluorescent lights when daylight levels exceeded target illumination.

The monthly gross sales per store were averaged over an 18-month period that went from February 1 of one year to August 31 of the following year. This average sales figure was transformed into a "sales index" that we could manipulate statistically, but that did not reveal actual dollar performance. Stores in the sample were selected to operate within a limited geographic region that had similar climatic conditions, and to have a constrained range of size and age. The geographic region has a relatively sunny climate. All of the stores in the data set are one story.

The multivariate regression analysis allowed us to control for the influence of other variables, which might influence sales. Other variables considered included the size and age of the store, hours of

operation, and economic characteristics associated with the zip code location.

Skylights were found to be positively and significantly correlated to higher sales. All other things being equal, an average non-skylit store in the chain would be likely to have 40% higher sales with the addition of skylights, with a probable range somewhere between 31% to 49%. This was found with 99% statistical certainty. After the number of hours open per week, the presence of skylights was the best predictor of the sales per store of all the variables that we considered. Thus, if a typical non-skylit store were averaging sales of \$2/sf, then its sales might be expected to increase to somewhere between \$2.61 to \$2.98 with the addition of a skylighting system.

The skylights are seen to have a major impact on the overall operation of the chain. Were the chain to add the skylighting system to the remaining 33% of their stores, their yearly gross sales are predicted to increase by 11%. The difference between having none of their stores skylit and all their stores skylit is a 40% increase in gross sales for the retail chain.

Footnotes:

[1] Heschong Mahone Group (1999). Daylighting in Schools. An investigation into the relationship between daylight and human performance. Detailed Report. Fair Oaks , CA.

[2] Heschong Mahone Group (2001) Re-Analysis Report, Daylighting in Schools, for the California Energy Commission, published by New Buildings Institute, www.newbuildings.org

[3] Fresno has nationally high levels of small particulate pollution associated with lung damage, per J Raloff "Air Sickness" in Science News, Vol 164, No 5.

[4] Heschong Mahone Group (1999). Skylighting and Retail Sales. An investigation into the relationship between daylight and human performance. Detailed Report for Pacific Gas and Electric Company. Fair Oaks , CA .

[5] Heschong Mahone Group (1999). Daylighting in Schools. An investigation into the relationship between daylight and human performance. Detailed Report. Fair Oaks , CA.

[Top](#)

<< [Back to Daylighting and Productivity](#)

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