Daylighting Impacts on Human Performance in School

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The purpose of this study was to see if we could demonstrate a clear relationship between the presence of daylight and human performance in buildings.

In this study we used a statistical technique called multivariate regression analysis, which analyzes the importance and impact of many variables simultaneously. The performance data used were gathered from three school districts. This analysis allowed us to estimate the effect of a wide number of variables and to determine which variables have no significant effect. Using this method, we established a statistically compelling connection between the presence of daylight and student performance.

The implications of the results of this study extend beyond the educational sector. We believe the conclusions may be transferable to other types of buildings, such as offices and factories, since it is really human performance we investigated. If daylighting enhances the performance of children in schools, it is not too large a stretch to suppose that it might also enhance the performance of adults in office buildings.

Background

Up through the 1950s and into the early 60s almost all school buildings in the United States were daylit, i.e., they were intentionally designed to provide sufficient interior daylight for normal daytime visual tasks. However, by the mid-1960s a number of forces came into conflict with the concept of daylit classrooms. Engineers, asked to provide air conditioning in classrooms, argued against the use of large expanses of glass and high ceilings. Educational theorists argued that a more flexible arrangement of open classrooms, grouped in large open-plan buildings, would encourage team-teaching and creative learning. Construction economists argued that schools could be built more inexpensively on smaller sites if the classrooms could be grouped together in modules, without constraints on solar orientation. Increasingly, schools were built with little or no daylight provided to the classrooms. In 1974, Belinda Collins of the National Bureau of Standards and Technology (NIST) conducted a major literature review of available research on windows, and concluded there was no conclusive evidence that windows were a necessary component of classrooms.[1]

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More recently, daylighting has been advocated as a way to reduce lighting energy use in schools and other non-residential buildings. Turning off electric lights when sufficient daylight is available can save a significant amount of lighting energy costs. Because daylight introduces less heat into a building than the equivalent amount of electric light, cooling costs can also be reduced with appropriate daylight design.[2]

Some studies have also suggested that the presence of daylight may have a positive impact on student performance and even health. A study done in Alberta, Canada termed "A Case of Daylight Robbery" has attracted both attention and controversy, claiming that student exposure to ultra-violet light, primarily through unfiltered fluorescent sources, improves student performance and health. The study unfortunately had many methodological flaws, including lack of control for daylight contribution to the various test sites and the use of high-pressure sodium lighting as the base case condition.[3] The terminology used in the Alberta study and others has contributed to a general confusion between electrically-generated full-spectrum lighting and naturally-generated daylight.[4]

A small but more carefully controlled study in Sweden found that observed behavior and circadian hormone levels of elementary students in classrooms with daylight stayed closer to expected norms than those in classrooms with only fluorescent sources.[5] The Swedish researchers concluded that windowless classrooms should be avoided. In the United States, a North Carolina architectural firm has received attention for reporting that student test score performance improved in their daylit schools compared to neighboring non-daylit schools.[6] While these studies all have methodological limitations, they have suggested a consistently positive effect for the presence of daylight on student performance.

We set out to see if we could establish a statistically significant association between daylight in classrooms and student performance.

Study approach

Elementary schools provide an ideal setting for a statistical study of human performance relative to specific building design characteristics. Within a given district, elementary school children are instructed following a highly standardized curriculum and are measured on their progress using standardized tests.

We chose to study second through fifth grade students in elementary schools because these students are generally assigned to a particular teacher in a single classroom for the school year. We felt that if the physical environment does have an effect on student performance, it would be most apparent in populations of elementary school students.

Public schools also collect extensive demographic information about the population of their students, which provided us with an economical way to control for many other variables that are widely recognized as important influences on learning.

We looked for districts where there was a wide range of daylight conditions. We specifically searched for districts that operated some classrooms with top-lighting.

We postulated that by including schools with skylights rather than daylighting from windows, we could better isolate the effect of daylight. Skylights generally provide a simple illumination function, whereas windows may have a far more complex effect on people. Windows typically offer a view, which may provide relaxation, inspiration or distraction. They are often operable, which may add ventilation, air quality, and thermal comfort issues. Daylight illumination levels from windows are highly variable within a space and over time, and may include components of unacceptable contrast and glare. User control of blinds or curtains also adds another dynamic variable that is difficult to measure. Windows are also connected with personal status, and may have psychological implications beyond their mere physical attributes. Skylights would not seem to be as imbued with as much cultural meaning and tend to have less variability in user control.

The study used multivariate linear regression analysis to control for other influences on student performance. These mathematical models allow us to isolate the effect of measures of daylighting, while simultaneously controlling for the influence of other variables. The models also provide measures of the statistical significance of each variable and the power of each variable in predicting results. This type of observational study is very useful in assessing the magnitude and statistical significance of a given effect. It cannot, however, prove any causal relationship.

The school districts

We were fortunate to find three school districts who met all of these conditions, and who were willing to participate in the study. The three districts—located in Orange County, CA; Seattle, WA; and Fort Collins, CO—have different curricula, administrative and teaching styles, different school building designs, and very different climates. This range of conditions provided us with an excellent opportunity to see if we could find a consistent daylight effect across a variety of conditions.

The Capistrano District, in Southern California, proved to be the most interesting for our analysis for a number of reasons. Capistrano had the most extensive student-performance and demographic data and the widest variety of daylighting conditions within classrooms. The Seattle and Fort Collins districts had similar data, but at a less detailed grain. Thus, the greatest focus of our analysis was on the Capistrano district.

The student-performance data available from Capistrano included comparison tests administered in fall and spring to measure student progress over the academic year. This eight-month measure of student academic growth, called Core Level Tests,[7] provided a very sensitive measure of how the physical environment might influence student performance. The analysis included data from 24 schools in the district.

In addition, Capistrano had the widest variety of daylighting conditions. The district included classrooms with few or no windows at all, aggressively daylit classrooms both from windows and a variety of skylights, and a considerable number of portable classrooms. These portable classrooms provided a serendipitous control for the analysis, since they were all similar, and occurred at every school site. Thus, each Capistrano school site had at a minimum of two, and often three or four, distinct daylight conditions. This variability of daylight conditions within each school site allowed us to statistically control for the effects of individual school sites—such as special programs, administrative or neighborhood effects—independent of the daylight conditions.

The Capistrano District is a rapidly growing district. As is common in California, all of its schools are single story and of relatively recent vintage. About three-quarters of the classrooms are not connected to interior corridors, forcing children to go outside for every errand outside of the classroom. The district is relatively affluent, with a demographic distribution of students that is 75 percent white, 17 percent Hispanic, and 8 percent other ethnic groups. Fifteen percent of the district students qualify for free or reduced lunches.

The Seattle District provided the second most interesting data. An urban district, it has over 60 elementary school sites, varying in age from recent to 90 years old. Many classrooms, especially those dating from the 1920s and 30s, had large clear windows providing high levels of daylighting. The district also has newer schools including a few open schools with few windows, some with top-lighting, and a few portables. The Seattle schools are designed for a rainy climate, with extensive indoor amenities. Many schools are two or three stories, with interior hallways connecting all facilities. In the Seattle data set, 53 percent of the students were classified as minority and 40 percent were eligible for a free or reduced lunch.

The Fort Collins district had the least variety of physical conditions and the least detail in the available student data. Of 21 elementary schools, seven had identical top-lighting systems in their classrooms. The other fourteen schools had only small to modest window areas. All have interior corridors. In the Fort Collins data set, 14 percent of the students were minority and 21 percent were eligible for a free or reduced lunch.

Each district provided us with extensive data bases, including math and reading test scores, attendance records and student demographic characteristics.[8] Demographic information included gender, ethnic background, and socio-economic status. The data included indicators of participation in special programs, such as bi-lingual programs or gifted and talented programs. Students in special education programs, where a substantial portion of the school day may be spent outside of the home classroom, such as for physical therapy, were dropped. Any student outside of the second to fifth grade range or with missing records was also excluded. Our final data-bases included about 6,000 to 8,000 students in each of the three districts.

The data for the Seattle and Fort Collins districts did not allow us to add a school-site variable to those models, since there was not sufficient daylight variation within each school. To probe for neighborhood biases in those districts, we interviewed administrators and local residents about the distribution of more daylit versus less daylight schools within more affluent vs. less affluent neighborhoods, and older vs. newer neighborhoods. In both cases we were convinced there was enough variation in the distribution of daylit schools across neighborhood types to continue with the analysis. We felt that the neighborhood effects were also likely to be reflected in variables defining the age of the school or in the socio-economic status of the individual students.

Defining the daylight variables

We created a second data set for each district describing the physical characteristics of each classroom.

Variables for all districts included the age of the school, classroom size, the type of the classroom, (traditional, portable or open), population of the school and classroom as well as the presence and size of windows and skylights.

It was a considerable challenge to characterize the daylight conditions in the 2,000 classrooms in these three districts. We encountered an enormous range of window and top-lighting conditions, which we had to reduce to a consistent scalar variable that could be used in the statistical analysis. Potential characteristics to be considered included window area, transmissivity, and configuration; room proportions and reflectances; window orientation, overhangs and obstructions; and local climate conditions.

After much discussion within the team, we decided the most we could hope to achieve in classifying the daylighting conditions was a simple bin scale from bad to excellent, based largely on the daylighting expertise of the team. The task was somewhat simplified since the analysis was within each district, rather than between districts. Thus, while it was essential that the assignment of codes needed to be consistent within each district, it was not essential that the codes be strictly comparable between districts.

We reviewed architectural plans, aerial photographs, maintenance records and visited a sample of the schools in each district to classify the daylighting conditions for each elementary classroom. Each classroom was assigned three codes: a Window Code (**Figure 1**) indicating the size and tint of its windows; a Skylight Code, indicating the presence and type of any top-lighting; and a Daylight Code (**Figure 6**), indicating the net amount of daylight expected in the classroom.

Window Code	Grade	Typical condition
0	None	None
1	Bad	One small window
2	Poor	A few small windows, tint
3	Average	Modest windows, and/or heavy tint
4	Good	Large windows, light tint or clear
5	Excellent	Large windows on two sides

Figure 1—Window codes.

The Window Code was based primarily on window size relative to classroom size, but with consideration given to the degree of tint of the glazing and any permanent obstructions that would clearly limit daylight penetration into the classroom, such as adjacent buildings or roofs. Thus, a classroom with windows that had a heavy tint or a major obstruction was downgraded by one code level.

The Skylighting Code was assigned according to top-lighting "types." Top-lighting conditions found within the three school districts were highly variable, with a variety of skylight and monitor designs employed. Some designs allowed direct sun into the classrooms while others were diffusing. Some were designed to provide uniform illumination throughout the classroom; others created strong illumination gradients.

Figure 2—Classroom with window Code 5.

Figure 3—Classroom with window Code 1.

Figure 4—Type A skylight, Capistrano.

There were five types of skylights employed in nine of the Capistrano schools. Two have a diffusing lens that spreads the daylight evenly throughout the classroom (such as Type A skylight in **Figure 4**), while three allow patches of sunlight to enter the classroom (Type B, **Figure 5**). Two of the skylight types are manually controlled, allowing the teacher to dim the daylight, while one type has dimming louvers controlled by an electric switch on the wall, and two others have no controls.

Seattle top-lighting types included skylights, east and south facing monitors and clerestories. Fort Collins had only one type, the south-facing monitor.

A Daylight Code combined the effects of both windows and skylights. It was assigned to each classroom based on a daylighting expert's assessment of the synthesis of the daylighting conditions expected from the combination of window conditions and any top-lighting found in each classroom. The criteria were based on

Figure 5—Type B skylight, Capistrano.

both the expected daylight illumination levels, and the uniformity of the illumination.

The highest Daylight Code, Code 5, was reserved for those classrooms that were designed so that a teacher could probably operate the classroom for most of the school year without using the electric lights. The next lower grade, Code 4, was assigned to classrooms where the teacher could occasionally operate without any electric lights. Code 3 indicated classrooms that might be able to turn some of the electric lights off occasionally. Code 2 classrooms would rarely, if ever, be able to operate successfully without all of their electric lights on.

Other physical variables

We measured both electric illumination and daylight illumination in a sample of classrooms from a variety of Capistrano schools. We found the electric illumination to be remarkably uniform, averaging 50 fc in almost every classroom. All electric lighting used 4 ft linear fluorescents, but with a variety of luminaire types and lamp/ballast systems.

We were not able to include analysis of the electric lighting system for a number of reasons. Unfortunately, none of the district data sets included information on classroom electric lighting systems. While architectural plans for the schools indicated luminaire type and spacing, many of these systems had been altered since original construction. Even within a given school or classroom, there were systems of different vintages and lamp/ballast combinations. Many classrooms, but not

Daylight Code	Grade	Criteria
0	None	None
1	Bad	Insignificant
2	Poor	Small areas of some daylight, glare from daylight sources
3	Average	Occasional, modest daylight in some areas, high contrast ratios
4	Good	Sufficient daylight sometimes, some areas, strong illuminance gradients
5	Excellent	Sufficient & uniform daylighting most of year

Figure 6—Daylight Codes.

all, had been recently retrofitted with T8 lamps and electronic ballasts. Thus, it was beyond the reach of this study to collect accurate information about the electric lighting system for every classroom, which could have been used as a variable in the analysis.

In Capistrano, we discovered that all skylit classrooms were also air-conditioned. Thus, we needed to control for the effect of air conditioning so we would not confuse any potential skylighting effects with air conditioning effects. We collected information about air conditioning type (new roof top, retrofitted roof top, wall-mounted, none) and natural ventilation (operable and non-operable windows) for each classroom.

Both Seattle and Fort Collins districts used 4-ft fluorescents almost exclusively, but we have no consistent information on their electric lighting systems. Air-conditioning is rare or non-existent in both districts, and so was not added to the models. Likewise we did not collect information about operable windows for these districts, but believe that most classrooms have some operable windows.

The Capistrano analysis

The school data were analyzed using four separate statistical models for each district, two using each student's reading scores as the dependant variable, and two using the math scores as the dependant variable. For each of the two dependant variables, one model was developed using the Daylight Code, and a second using the Window and Skylight Codes. Thus, a total of twelve models were created across the three districts.

The statistical models for the Capistrano district were developed to predict the change in student test scores from fall to spring. The analysis addressed more than fifty potential explanatory variables, including all the demographic information about each student, the physical characteristics of each classroom and a dummy variable that identified each school site.

A step-wise regression methodology was used to identify the statistically significant variables for inclusion in the model. Criteria for variable inclusion in the models were a minimum 90 percent statistical significance for non-daylight variables, and 95 percent significance for daylight-related variables. For each model, outliers were identified and excluded. The coefficient of determination (R^2) for the four Capistrano models varied from 0.246 to 0.258, indicating that about 25 percent of the variation in student progress could be explained by these models. This is reasonably high for a statistical model attempting to explain highly complex individual student behavior.

Figure 7 details the variables included in one of the models, the Math-Daylight Code model. The chart lists the significant variables in their order of entry into the model. Those that enter first are the most statistically significant for explaining differences between students in the dependent variable – the change in student test scores from fall to spring. The B coefficient measures the magnitude of an effect for each variable. Identification of school sites has been disguised. Variables named with just a number are student outliers, also disguised. Significant variables varied slightly between models. All statistical results and descriptive characteristics are included in the appendix of the project's final report.

Capistrano findings

Figure 8 summarizes the increases in test scores for the daylighting-related variables for all four Capistrano regression models. The Capistrano Core Level Tests are reported on a special scale system called "RIT." The average student in our data set progressed in reading scores by 8.8 RIT points and in math scores by 12.5 points from fall to spring.[i] For the charts in this report we have translated all the test results into a consistent scale of 1-99 in order to facilitate comparison between the districts. We also report the test results as a percentage effect to show the relative magnitude of the findings. The Daylight and Window Codes are compared from the minimum to the maximum condition. All others are yes/no variables.

Daylighting was found to have a considerable effect in the Capistrano schools. The Daylight, Window and Skylight Type A variables were all positive and highly significant, at greater than 99 percent statistical significance.

The following bullet points summarize these Capistrano findings:

- The classrooms with the highest Window Code were found to be associated with 15 to 23 percent faster rate of improvement over a one year period when compared to classrooms with the lowest Window Code.

i These values are averages for our specific data set, not the district, because our data set was a sub-set of all students in the district. For the percentage effects discussed here, the raw RIT score (not the normalized score shown in the chart) was divided by the average from our data set.

Variable	B	Order of Entry	Change in R^2
Grade 2	9.741	1	0.149
Grade 3	5.929	2	0.064
32	62.456	3	0.007
Grade 4	1.811	4	0.006
48	-46.423	5	0.004
GATE prog	-1.237	6	0.003
45	-40.309	7	0.003
Daylight Code	0.504	8	0.003
Sch 72	-1.614	9	0.003
18	35.115	10	0.002
02	-34.466	11	0.002
33	34.059	12	0.002
Sch 59	-1.090	13	0.001
Absences Unverified-per 10	-2.636	14	0.001
Sch 62	1.446	15	0.001
Sch 77	1.166	16	0.001
Sch 82	1.197	17	0.001
Sch 61	0.897	18	0.001
School pop-per 500	-0.508	19	0.001
Lang prog	0.492	20	0.001
Sch 67	0.897	21	0.000
Sch 71	0.803	22	0.000
Absences Unexcused-per 10	-0.260	23	0.000
Operable Windows	0.249	24	0.000
(Constant)	8.022		
		Model R^2	0.257

a. Dependent Variable: MATHDELT

Figure 7—Capistrano Math-Daylight model.

- The classrooms with the highest Daylight Codes were found to be associated with 20 to 26 percent faster rate of improvement when compared to classrooms with the lowest.
- The classrooms with the Skylight Type A were found to be associated with a 19 to 20 percent faster improvement when compared to classrooms with no skylights.
- Classrooms with operable windows were found to be associated with 7 to 8 percent faster improvement in three out of four cases, when compared to classrooms with fixed windows.
- However, the classrooms with the Skylight Type B were found to be associated with a 21 percent decrease in reading tests, and no significant difference in math tests, when compared to classrooms with no skylights.

Skylight Type A had the most even light distribution of the five skylight types, fully diffused without any potential for direct sunlight to enter the room. It also allowed the teacher to control the amount of daylight with the use of manually controlled louvers.

Skylight B had no diffusion or control, allowing patches of direct sunlight to strike the walls or student desks. While it provided relatively high daylight illumination on vertical surfaces, the potential for glare and thermal discomfort from the sun patches was considerable.

The observation that both the Daylight variable and the Skylight Type A variable have slightly larger effects than the Window Code argues for the conclusion that the presence of daylight in and of itself, and not view or other aspects of windows, are responsible for the positive effects.

Operable windows were also found to have a significant positive coefficient for three out of four of the Capistrano models. We posit that allowing the teacher the option of using natural ventilation when desired is a positive feature for classrooms. There are many possible interpretations of these findings, including interactions with other variables, the mild climate in Capistrano, or air quality issues. We would suggest that this finding deserves further study.

The other districts

We performed a similar analysis for the other two school districts in Seattle and in Fort Collins. The Seattle and Fort Collins districts did not administer repeated testing within the school year. Thus, these studies used the absolute value of the students' 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.

The Seattle district

Seattle Public School District is a primarily an urban school district in the city of Seattle, WA. Elementary schools in Seattle tend to have far fewer students than Capistrano, and a great deal more floor space per student, with interior corridors connecting all rooms.

Most Seattle elementary schools have substantial windows with clear glass, especially those built in the 1920s and 30s (**Figure 9** and **10**). Some of the newer schools have lightly tinted glass and a few have minimal or no windows. There are a few open schools from the 1970s with "pod" classrooms that share a common space in the center. These open classroom schools typically have few, if any, windows. Some schools are clearly designed for full daylighting, with high ceilings (11 ft) and window walls on two sides of the classroom.

In four of the schools, daylight was also provided from clerestory windows high up in the walls, saw-toothed

Capistrano	Analysis Results				Percentage Effect	
NEA Core Level Tests Range: -29 to +79	Difference in Average Test Improvement (normalized RIT points)		Statistical Certainty		Difference as a % of District Average Improvement	
Change, Fall to Spring	Reading	Math	Reading	Math	Reading	Math
Model 1						
Daylight, Min. to Max.	2.8	2.3	99.9	99.9	26%	20%
Operable Windows	0.8	-	99.8	n/s	7%	-
Model 2						
Windows, Min. to Max.	2.4	1.7	99.9	99.9	23%	15%
Skylight A	2.0	2.3	99.7	99.9	19%	20%
Skylight B	-2.2	-	94.9	n/s	-21%	-
Operable Windows	0.9	0.8	99.6	99.9	8%	7%

Figure 8—Summary daylight findings for Capistrano.

Figure 9—Older Seattle school, Window Code 4.

Figure 11—Seattle classroom with clerestory windows.

Figure 10—Older Seattle school, Window Code 4.

Figure 12—Seattle school with central skylight and diffusing louvers.

monitors or skylights. One school with open-type classrooms has high clerestory windows that allow daylight deep into the building (**Figure 11**).

The Seattle district provided us with student scores for the Iowa Test of Basic Skills (ITBS) administered in the spring. The demographic and physical condition variables were also slightly less detailed then at Capistrano.

The Fort Collins district

The Poudre School district in Fort Collins, CO is a rapidly growing school district about two hours north of Denver. The district has many new facilities, some of which include aggressively daylit classrooms which are lit from south-facing rooftop windows, or sawtooth monitors. Although they diffuse the sunlight somewhat, they are very bright. On a sunny day horizontal illumination levels were measured to vary from 40 to 500 fc. Teachers have the option of pulling an insulating shade across the skylight to darken the room. On one partly sunny winter day, we observed that 60 percent of classrooms had their shades closed.

These skylit schools have modestly sized windows. Other older schools without the sawtooth monitors have somewhat larger window areas. However, none of the Fort Collins schools have classrooms with the very large windows designed for complete daylighting, as we found in the Capistrano or Seattle districts.

Due to the structure of the data sets given to us by Fort Collins, we were not able to identify students by their specific classroom location, but only by their grade level within a school. As a result the final analysis in Fort Collins was much simpler and more general than the other two districts. Luckily, most schools in Fort Collins had fairly uniform daylighting conditions for all their classrooms. Thus, an overall school daylighting code was a reasonable approximation of individual classroom conditions.

Seattle and Fort Collins findings

Both the Seattle and the Fort Collins analyses found a similar pattern of positive, significant results for the daylighting variables. These results were not only significant, but remarkably consistent in magnitude across all models.

It should be remembered that these results are from different tests with different scales. The Seattle tests used a scale called Normal Curve Equivalent, which ranges from 1-99. The Fort Collins tests used the same RIT scale as Capistrano. We have put all the test results in our graphs on the same 1-99 scale in order to make the results between districts as comparable as possible. Also, these two districts results are not a rate of improvement based on the change between fall and spring, as in Capistrano, but rather an absolute level of test scores taken at the end of the school year.

Figure 15 summarizes the percentage effects for the daylighting related variables of the four Seattle models. All these variables were found to have 99 percent statistical significance. All other things being equal, students in classrooms with the largest window area, or the most day-

Figure 13—New Fort Collins' school with saw-tooth roof monitors.

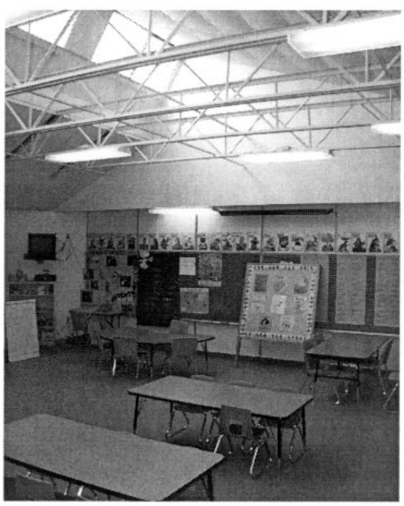

Figure 14—Interior of Fort Collins school with south-facing monitor.

light, were found to be testing 9 to 15 percent higher than those students in classrooms with the least window area or daylighting. A 6 to 7 percent effect is observed for the skylit classrooms.

The Fort Collins results in **Figure 16** show a 7 percent improvement in test scores in those classrooms with the most daylighting, and a 14 to 18 percent improvement for those students in the classrooms with the largest window areas. There is a three percent effect for math scores in the classrooms with the roof top monitors and no significant effect on reading scores.

The Fort Collins results may be influenced by a number of factors that are distinctive about this district. First of all, we had the least amount of information about the characteristics of the students and schools in the Fort Collins district. Of the three districts studied, there is the greatest likelihood that there may be other unknown

Seattle ITBS Iowa Test of Basic Skills NCE Scale 1-99	Analysis Results Difference in Average Test Scores (NCE percentage points)		Statistical Certainty		Percentage Effect Difference as a % of District Average Score	
Spring Scores	Reading	Math	Reading	Math	Reading	Math
Model 1						
Daylight, Min. to Max.	7.5	5.6	99.9%	99.9%	13%	9%
Model 2						
Windows, Min. to Max.	7.7	8.7	99.9%	99.9%	13%	15%
Skylights, Min. to Max.	3.9	3.4	99.9%	99.8%	7%	6%

Figure 15—Summary findings for Seattle.

variables that influenced the findings.

Secondly, the district has only a modest range of window conditions. There were no classrooms in Fort Collins without any windows, and no classrooms with really large window areas, or what we considered full daylighting.

Finally, the skylighting variable is considerably weaker in these models than in Seattle, having only a small positive magnitude for math, and no significance for read-

Fort Collins NEA Core Level Tests Normalized Scale 1-99	Analysis Results Difference in Average Test Scores (normalized RIT points)		Statistical Certainty		Percentage Effect Difference as a % of District Average Score	
Spring Scores	Reading	Math	Reading	Math	Reading	Math
Model 1						
Daylight, Min. to Max.	3.8	3.4	99.9%	99.9%	7%	7%
Model 2						
Windows, Min. to Max.	10.2	7.0	99.9%	99.9%	18%	14%
Skylight Monitor	-	1.6	n/s	99.7%	-	3%

Figure 16—Summary findings for Fort Collins.

ing. We believe the weak positive effect of the skylight variable may be a function of poor lighting quality from the south facing monitors, and the observation that many teachers seem to keep the shades down to solve this lighting quality problem. One would expect skylights that are closed off much of the time would not have much of an effect.

The results for the daylighting variable are probably also depressed for the same reason, since the daylighting code was largely a function of the skylighting code. We assigned the classrooms with skylights the highest daylight code for our analysis, on the expectation that they would have the highest daylight illumination levels. We didn't know the extent of the glare problems or the operation of the shades until after the analysis was completed. Ideally, a daylight variable would be based on observations of daylight illumination conditions throughout the school year.

Possible daylight mechanisms

This kind of statistical analysis cannot prove that skylighting causes improved student performance. It can only demonstrate that there is a strong correlation between the presence of skylighting and higher test scores. The reason for the effect is left to hypothesis at this point.

Many possible mechanisms for daylighting effects on human behavior have been suggested. For the schools study, these can generally be summarized as improved vision, improved morale, and improved health. Such a daylight effect might be a function of any one, or any combination of the following:

- Improved vision due to:
  - Higher illumination levels under daylight
  - Better color rendition under daylight
  - Improved spectral content of daylight (scotopic enhancement)
  - Improved three-dimensional modeling with high lights and shadows
  - Reduction of flicker effects from electric lighting

- Improved student and/or teacher morale or performance due to:
  - Mental stimulation from varying lighting conditions
  - Calming effect of a connection with the natural world (weather, time of day)
  - Greater mental alertness due to circadian biochemical responses to daylight (neurotransmitter levels)
- Better memory retention due to one or more of the above processes
- Improved longer term health due to circadian biochemical responses to daylight

Capistrano students are likely to have extensive exposure to daylight outside of the classroom, both after school and many times during the school day as they navigate the school facilities. Thus, it would seem likely that any daylight effect must involve a fairly short term mechanism, during the 1-2 hours they are continuously in a classroom, rather than any longer term mechanism, such as overall health, that would integrate all exposure to daylight over weeks or months. Thus, improved vision and/or morale would seem to be the most likely mechanisms for daylight to affect these elementary students.

The argument might by made that the presence of daylight in the classroom influenced test performance, via better visual conditions, rather than learning. We doubt that this is the case, since our metric for Capistrano was improvement in test scores from fall to spring, instead of absolute test scores. While we do not actually know where the tests were administered, it is our assumption the majority were taken in the classroom, as is the common practice in most American elementary schools. Thus, assuming that both fall and spring tests were taken in the home classroom, they would have both been subject to similar lighting conditions, and we would not have seen a visual performance effect for the test, but the net effect of learning over the eight-month period between tests. The tests were not administered on the same day throughout the district, making it less likely that weather conditions were a factor.

Teacher assignment bias

Critical review of the findings reported above raised the question: "Are the improved student scores a function of daylight in the classroom, or more skilled teachers being preferentially assigned to the daylit classrooms?" We have attempted to answer this question for the Capistrano District with a variety of approaches.

First, we interviewed administrators and principals in the district, who assured us there was no obvious mechanism or practice of assigning "better" teachers to more daylit classrooms. Indeed, given the rapid growth of the district, frequent reassignment of classrooms to accommodate new school openings and added portable classrooms tended to randomize teacher classroom assignments on a fairly regular basis.

Next we re-analyzed the original Capistrano data aggregated at the classroom level, rather than treating each student's performance as an independent event. If student performance were more influenced by being together in a classroom group or having a particular teacher, then the variance in student performance between classroom groups should be larger than the variance between different daylighting conditions.

Figure 17 compares the results of the classroom-level analysis with the original student-level analysis. The table shows the regression output for the Skylight Type A explanatory variable for the math and reading models. Other variables had similar results.

The following points are important to note:
- The B-coefficient remained stable. The math coefficient dropped slightly but the reading coefficient rose a fair amount. Neither change was statistically significant.
- The standard errors increased, as expected, given about a 20-fold decrease in the number of records.
- The t-statistics fell and the significance levels became somewhat poorer. But both variables are still highly significant.

In developing the classroom analysis, we estimated the components of variance associated with common classroom factors and student-specific factors. In the case of math performance, the classroom component of the variance was about 20 percent of the total variance, while the student component of the variance was about 80 percent. In the case of the reading model, we found no classroom component of variance. We may postulate that the classroom effects are associated with differences between teachers. In this case, these results suggest that Capistrano teachers are uniformly good at teaching reading but have more variation in their ability to teach math.

Math	B	Std Err	t	Sig
Student Level	2.556	0.469	5.449	0.000
Class Level	2.451	0.830	2.953	0.003
Reading	B	Std Err	t	Sig
Student Level	1.668	0.560	2.979	0.003
Class Level	1.932	0.728	2.655	0.008

Figure 17—Classroom vs. student level results.

One year after the original analysis, we surveyed 250, or about 40 percent, of the Capistrano teachers in the original study, collecting additional information about their years of teaching experience, education levels, credentials, awards and classroom preferences. Forty-one percent of the teachers surveyed felt they might have had some influence on the selection of their classroom within the past five years. Windows or natural light was indicated by seven percent of the sample as their most important criteria for selecting a classroom. Windows were ranked among the top three most important criteria for selecting a classroom by 20 percent of the sample, after classroom size (53 percent), convenient location (36 percent), storage capacity (30 percent), running water (24 percent), and quiet location (23 percent). Thus, while teachers differed with the administrators in believing they did have some influence in the selection of their classroom, windows and natural light were not the most important criterion for their selection.

Finally, a regression analysis of the daylight code for the teacher's assigned classroom as the dependant variable was run against teachers' years of experience, education level, special credentials and awards as explanatory variables. This model was run using only the surveyed teacher population. This model would tell us more precisely if there was indeed an "assignment bias," such that some teacher types were more likely to be assigned to daylit classrooms.

From this regression model, we found there were no teacher characteristics, as defined by our variables from the survey data, that were significant in explaining assignment to more daylit classrooms. The variable that achieved the highest probability of influence was Teacher 7 (honors) at only 78 percent likelihood of significance (p=0.22) that there might be a 5 percent higher assignment in Daylight Code (A teacher who had received an honor or award had a 78 percent probability of being assigned to a classroom rated 3.15 on the daylight scale instead of a 3.0). The other variables had a 50 percent probability or less.

The R^2 for this model was only 0.014, indicating that all of the teacher characteristic variables could explain only one percent of the variation in assignment to daylight classrooms. When we ran a similar model at the student level, the level of explanation increased to two percent. Thus, from this exercise we conclude the Capistrano Unified School District did not have any marked bias in the assignment of teachers to more daylit classrooms, based on the teacher characteristics that we studied.

Our next analysis effort will be to include teacher experience and credentials in the original model, to see how important those variables are in predicting student performance relative to the daylighting variables.

Conclusion

We have performed a statistical analysis relating standardized math and reading test results of a large population of students to the lighting conditions of their classroom with controls for other factors such as teacher experience and the demographic characteristics of each school. We were able to identify statistically significant effects of daylighting on human behavior, as evidenced in the standardized test scores for elementary school students. These studies provide a useful gauge of the potential magnitude of such effects.

The consistency of the findings across the three school districts, and in a separate study of another building type, a retail chain, strongly suggest there is indeed an important daylighting effect associated with increased window or skylight areas in buildings.

The studies do not, however, offer any explanation of why such an effect would occur. Nor do they prove a causal relationship: it remains unknown if it is indeed the daylight, or some other tightly associated condition, which is causing the observed effects. Likewise, the addition of additional explanatory variables, such as teacher education or experience, is likely to somewhat reduce the magnitude of any effect.

Three potential pathways are suggested for a daylight mechanism that improves human performance: increased visibility, enhanced mood and improved health. All three are under investigation by other researchers. It will certainly require a coordinated strategy using a combination of methodologies—laboratory experimentation, field work, and population studies—to clearly delineate a mechanism. Further studies will hopefully be able to quantify effects from other, more precisely defined, aspects of the luminous environment, and eventually create linkages to specific causal mechanisms.

Acknowledgements

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Pacific Gas and Electric (PG&E) Daylighting Initiative. The additional analysis discussed in this paper is reported in the "Re-analysis Report," also supported by the PIER program. In addition to the authors listed, Barbara Erwine, Neal Digert and Kris Baker contributed to the data collection and daylight analysis in the study. We thank all of the many reviewers who contributed comments and guidance to both the original PG&E research and the CEC Re-Analysis Study.

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8. Protection of privacy was a consideration in all analysis. Individual student identities were masked by substituting false student record numbers for all data sets. In addition, some districts decided to provide some demographic data at a classroom level to further mask individual student records. Similarly, in our reporting, we scrambled the identification numbers for school sites, and renamed the some demographic variables to make them generic.

9. These values are averages for our specific data set, not the district, because our data set was a sub-set of all students in the district. For the percentage effects discussed here, the raw RIT score (not the normalized score shown in the chart) was divided by the average from our data set.

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Discussion

In 1993, Wang, Haertel and Walberg published a classic synthesis of meta-analyses concerning the factors that affect school learning. The most influential were the characteristics of students, such as motivation and cognitive abilities, and the classroom practices of teachers, such as classroom management and quantity of instruction. From the viewpoint of educational psychology, Heschong, Wright and Okura's findings break this mold, both by examining a different kind of variable, and by showing that it affects learning.

Heschong, Wright and Okura's use of three large, diverse samples of schools provides a strong data-base. They obtained information on a variety of student and institutional variables, and used multiple regression to separate their effects from those of daylighting. They appropriately used a conservative procedure by setting a more stringent criterion for the inclusion of daylighting variables than for other variables. And the similarity of the results obtained in two subjects and three different districts provides crucial replication.

In spite of the generally high validity of the study, the size of the effects is difficult to interpret. For example, in the Capistrano data, the percentage effects seem large, e.g., a 20 percent increase over district average improvement for math (**Figure 8**). However, the gain in RIT was only 2.3 points in math (**Figure 8**), and when daylighting was entered into the regression model, the change in variance accounted was only 0.003 (**Figure 7**), suggesting a small effect size. In any case, more information is needed concerning the Capistrano and Fort Collins tests. The Iowa Test of Basic Skills provided more interpretable data for the Seattle sample, and seems to indicate larger effects. However, even if the effects of daylighting are modest, they may be educationally useful, given that they appear to supplement the effects of other variables, and may accumulate across years of education.

The authors have used perhaps the most rigorous methodology practical for this problem at the present time, and they have willingly acknowledged that regression analysis does not prove causal claims. However, few previous studies have examined the effects of daylighting on learning, and the findings in this study are somewhat unusual, e.g., in the Capistrano Math-Daylight Model, daylighting contributed more variance than other seemingly important student and instructional variables (**Figure 7**). These unexpected findings invite further validation. First, it would be beneficial to examine some alternative mathematical models, for example, entering student and instructional variables first, then, testing the effects of daylighting variables. And finally, before any schools are specially designed or retrofitted to increase daylighting, a controlled experiment will be essential. In the meantime, this study contributes to educational research by making a convincing initial case for the effects of daylighting on learning.

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Ontario, Canada.

While the authors controlled, statistically, variables that could have contributed to their findings, one not mentioned was the curriculum. Even within a given school district there could be considerable variation from school to school in the way reading is taught. Some teachers might adhere to a child-centered whole language curriculum, whereas others will employ a more phonics-based approach to reading. Differences of this nature often occur even though all of the children in a given district receive a common exam at the end of the year. The outcome of these differences is that children in certain schools perform better than children in other schools (for example, Evans, M.A., 1985 *Impact of classroom activities on beginning reading development.* In T.H. Carr, Ed., *The development of reading skills. New Directions for Child Development.* No. 27, San Francisco, CA, Jossey-Bass).

Unless the authors also control for curriculum differences, any school-to-school comparisons are difficult to interpret. Gathering information on years of teaching experience, education levels, credentials, awards and classroom preferences, unfortunately, does not address this issue. Neither does incorporating data into the statistical analysis on attendance records and demography including gender, ethnic background and SES.

There are other variables associated with test performance that could lead to different scores among schools: high expectations for students, clear instructional objectives, close monitoring of student achievement, strong principal leadership and a safe and orderly school climate (Lytton, R. and Pyryt, M. 1998. Predictors of achievement in basic skills: A Canadian effective schools study, *Canadian Journal of Education*, pp. 23 and 281-301).

I congratulate the authors on performing an extremely ambitious and most interesting study. I hope they will be able to include further data on the variables mentioned in a subsequent analysis of their results. If the findings continue to demonstrate that there is a strong correlation between the presence of day lighting and high test scores when each of these other variables are considered, I'm certain the educational community will be most appreciative of their contribution.

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The authors state that in the classrooms considered, the electric lighting consistently averaged 500 lx, so we conclude that the daylight variable is a measure of the light level above a base of 500 lx. Performance is expected to improve with increased light level, but the amount of improvement might be insignificant or even non-existent, especially if the base level is already fairly high, or if the increased light levels are associated with increased glare, or heat or some other distraction. The authors' study appears to show the increased lighting in schools is significant, but unfortunately the analysis presented here is sufficiently obscure so that the reader has difficulty in accepting the conclusions with confidence. The authors make little attempt to provide a context and an appreciation for their quantifications.

We learn from **Figure 7** that the Daylight Code effect explains only 0.3 percent of the variance and among the various factors considered by the authors as explanatory, the Daylight Code effect represents only a 1.1 percent contribution. Thus the Daylight Code on the whole is a very small factor among the factors that are considered to affect score differences. Nevertheless the authors argue that the effect is significant. It is therefore disturbing that a separate entry for a single student (#32) explains twice as much of the variance as the Daylight Code. The report needs a sensitivity analysis to provide the reader with an assurance that the supposed significance of the Daylight Code is not due to a small number of anomalous students with R^2 in the 0.001 range or slightly smaller.

We learn in the section 'Capistrano Findings' (the most important of the results) that on the average, the overall district 'RIT' scores improved 8.8 RIT points in reading (out of a possible total not given). In **Figure 8** the analysis is reported in terms of a normalized RIT scale, and in **Figure 7** the variables are described in terms of their B coefficients. The report does not describe how these quantities are related. It would be helpful if the report gave the possible and observed range on the original and normalized RIT scales, along with the means and standard deviations. It would also be useful if the authors provided the original RIT scores for each of the daylight codes. In this way the reader would be able to see directly the principal effects.

In **Figure 7** the B scores decrease as the grade levels increase. In addition, the B score is negative if the school has a GATE program, which is a program for gifted students. The authors do not list the means by grade, nor do they list the possible range, so it is not possible to determine if the smaller scores at higher ability levels are due to there being less potential improvement. Whatever the reason, this trend raises the possibility that a weak daylight effect may be due to a correlation or interaction of daylighting with grade or overall performance level. Does the effect remain present if the analysis is separated by grade levels? It would help if the authors presented the RIT scores, and not just the differences, as a function of the different independent variables.

It is also surprising that the authors' did not find a teacher effect for the reading evaluation. Would the authors comment on whether this conclusion is supported by other literature?

The authors do not discuss other statistical matters that could be of importance and would instill a higher confidence in their conclusions such as the degrees of freedom and the possibility of various interactions between variables.

Given all the effort expended in the gathering of data and carrying out the analysis, the authors would add significantly to the credibility of their results if they would provide a more transparent report considering the lighting practice community as their audience.

Sam Berman Ph.D. and Robert Clear Ph.D., Lawrence Berkeley National Laboratories, Berkeley, CA

Authors' response

To Perry Klein

We acknowledge that the change is R^2 for the daylight variable is seemingly small (0.003), but it is comparable with other variables widely acknowledged to be educationally important, such as participation in a gifted and talented program (GATE R^2 = 0.003), number of absences (R^2 = 0.001), or size of school (school pop per 500 R^2 = 0.001). This would seem to put daylight in the mix of educationally important variables.

More information is available about the Capistrano and Fort Collins tests through the Northwest Educational Association (www.nwea.org), the non-profit association that develops standardized tests for 650 school districts around the country. We worked with their director of research, Gage Kingsbury, to make sure that our analysis techniques were appropriate to their reporting protocols.

We appreciate the suggestion to pursue further validation and alternative mathematical models. We will be doing a similar, but more detailed study of another school district, courtesy of funding from the California Energy Commission Public Interest Research Program (PIER) and will adopt your suggestion to enter student and instruction variables first, before testing the daylight variables.

To Marvin Simner

Dr. Simner suggests the study did not control for curriculum differences between teachers. The desire to control for differences in educational approach is one reason why we choose to examine three districts, but modeled each one separately, on the assumption that curriculum differences between districts would be too great to be controlled for in a single study. In an effort to understand the potential for curriculum differences with districts, we also interviewed district administrators. We paid the closest attention to the Capistrano district, where we learned that a uniform teaching methodology is strongly encouraged, and reinforced with in-district training courses and support materials. Indeed, our classroom level analysis (**Figure 17**) shows that the district has little variation in reading instruction capabilities between teachers. We found more variation in the teaching of mathematics.

We also controlled for any curriculum differences across schools, but within a district, by including a school-site variable in the Capistrano models for each school. Any significant differences in curriculum styles between individual schools within the Capistrano district should have been absorbed by the influence of these school-site level variables. There were also additional multi-school variables included in the models, such as bilingual programs and year-round schedules that were shared by three or more schools within the district. Similarly, any of the other school-wide differences that you mention, such as strong principal leadership, safe and orderly school climate, or PTA volunteerism, should be captured by the school-site variables. We were not able to do such fine level of analysis for the Seattle or Fort Collins studies, but do hope to continue to control for such variations between school and teachers within a district in any future studies.

To Sam Berman and Robert Clear

Drs. Berman and Clear request further clarification on the illumination levels in the classrooms studied. We took daylight and electric illuminance readings at a sample of classrooms in each district. Electric illuminance levels were consistently around 500 lx (+/- 200 lx). Daylight illuminations were far more variable, both across classrooms and within a classroom, ranging from 5 to 5000 lx. We did not attempt to statistically describe any of this variation, or try to describe operating light levels in the classrooms for two reasons: 1. We did not have sufficient funds to sample enough classrooms. 2. Our analysis was based on a one year period of classroom operation, but our site visits were for only one point in time. We did not have any information about how the teachers actually operated their classrooms—when they might have turned the electric lights on or off or when they modulated the amount of daylight in the classroom. So, similar to the "operable windows variable" that we created for Capistrano, the daylight code is merely an indicator of the potential for daylight in the classroom, not of actual illumination levels or daylight conditions over time. The daylight code was not based on daylight illumination measurements, but rather expert evaluation of the classroom geometry and fenestration to estimate, on a scale of 0-5, the overall quantity and quality of daylight available over time for a given classroom.

We refer you to our response to Perry D. Klein, Ph.D. on the issue of small R^2 for the daylight code. The high R^2 for a single student is precisely why a number of students were identified in the analysis as "outliers" and mathematically isolated from the model. The norm of change in test scores for the district was 8.8 for reading and 12.5 for math, but could potentially range up to 100 points if a student had one really bad test. Identifying and isolating outliers is standard statistical practice to avoid exactly what you are concerned about, that one or two exceptional students would unduly affect the results.

Relative to your comment on reporting format of the RIT scores, we struggled with the best way to report our findings across districts which used different test reporting formats. To help the reader of this short article make comparisons across districts we chose to normalize the results to a 1-100 scale across districts. However, all original data is reported in its raw form in the appendices of the original report, along with descriptive statistics for each data set analyzed. The reader is invited to correspond with the authors if he or she wishes to obtain a copy of the original report and appendices.

You make a very interesting comment about grade levels. We too were concerned that the results reported could conceivably be a result of interaction between grade level and daylight. For example, if second graders consistently make more progress per year, and more second graders are placed in daylight classrooms, then we might see the daylight code being artificially inflated by the second grade effect. Alternatively, if second graders are more sensitive to a "daylight effect", that might also inflate the daylight effect overall by including higher levels of progress for second graders. It was also postulated that students, who spent their entire elementary school career in daylit classrooms as was possible in Seattle, might exhibit a "progressive effect" of greater improvement every year. To address this issue we went back to the original data for Seattle and Capistrano and re-ran the models with interaction variables included for every possible variable-grade level combination. The findings of this grade level analysis are reported in a publicly available follow-on report.[10]

In Capistrano, out of twelve opportunities, the interaction between grade level and daylight was found to be significant in only one case. In Seattle, when allowing for grade level interactions with all the other model variables, we saw no declines in significance, and also saw substantial increases in the magnitude of the daylight effect. In the case of the Seattle reading model, the magnitude of the daylight effect increased 26 percent, while in the math model the magnitude of the daylight effect increased 12 percent. For the Seattle reading model, the accuracy of the model (R^2) increased 4 percent. This would tend to argue for the validity of the increase in the magnitude of the daylight effect.

The grade level analysis did not increase the accuracy of the Capistrano models. Furthermore, while we did find interaction effects between grade level and other variables, most notably the demographic variables, we did not find a consistent interaction between grade level and a daylighting effect. This was true in both Seattle and Capistrano.

From this exercise, we conclude that our original modeling approach, grouping all of the data for grades 2-5, was sufficiently accurate. We also note that we did not find any progressive effect for the daylighting variable, as postulated for Seattle, nor any other pattern related to the age of the student.

Berman and Clear requested a comment on the lack of teacher effect for the reading evaluation. Our conclusion is, "these results suggest that Capistrano teachers are uniformly good at teaching reading but, have more variation in their ability to teach math." Administrators in the Capistrano district interpret these results as validation of their aggressive reading methods teacher-training program. We have no idea if such findings would be replicated in other districts.

Regarding further information on statistical metrics, the reader is again referred to the original detailed report and appendices. The degrees of freedom in the student-level analysis were extremely high, given that we were dealing with a student population of 8000-9000. However, even when we performed the classroom level analysis, the degrees of freedom were still quite high, given 300 classrooms and 50 variables in the model. The classroom level analysis suggested that the decision to analyze the data at the student level was appropriate given that at least 80 percent of the variation in data is at the student level.

We are continuing to try to explain this rather complex study as quickly and clearly as possible. We appreciate the suggestions on how to do it better, and hope that in our future studies we will be able to address more questions the lighting community may have about daylighting and its effects on human performance.