Daylighting and Productivity: Elementary School Studies

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ABSTRACT

In this paper we will report on the methodology and findings of a project that found a statistically compelling connection between daylighting and student performance.

We analyzed test score results and demographic data for over 21,000 students from three elementary school districts, located in California, Washington, and Colorado. Over 2000 classrooms were categorized on a simple 0-5 scale indicating the size and tint of 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, with up to 50 variables considered. The three districts have different curricula and teaching styles, different school building designs and very different climates. Yet the results of the studies consistently show a positive and highly significant association between increased daylight and improved student performance on the tests.

In the California district, students with the most daylighting in their classrooms progressed faster on math and reading tests between fall and spring than those with the least daylighting. Similarly, larger window areas, well-designed skylights and operable windows were also associated with faster student progress, all with high degrees of certainty. In the Washington and Colorado districts, we found similar results when looking at absolute test levels rather than progress from spring to fall. The study has important implications for the design of energy efficient school buildings, and when considered in the context of other evidence linking daylighting and productivity, other commercial facilities[1].

Daylighting in Schools

This study examines the effect of daylighting on one aspect of human performance. The study looks at how daylighting, from windows or skylights, affects the test scores of students in three elementary school districts. We found a statistically compelling connection between daylighting and improved student performance.

Schools were chosen as the subject of the study because we could obtain extensive data on occupant performance for nearly identical buildings. We believe that the conclusions may be transferable to other types of buildings, such as offices and factories, since it is really human performance that we are investigating. 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. If daylighting motivates buyers at a retail store, it is not too large a stretch to presume that it might also motivate workers in a factory.

[1] A related study (Okura et al, 2000) reports on how the use of skylighting affected the sales of a large chain retailer.

Background

The impact of daylighting on the performance of school children has been a subject of interest for many years. Before fluorescent lighting became prevalent, it was generally assumed that all school rooms would be daylit as a matter of course. The California Department of Education had a rigorous review process for the architectural design of classrooms to ensure that daylighting standards were met. As a result, California classrooms built in the 1950's and early 1960's remain excellent examples of daylighting practice. The "finger" plan with multiple rows of single classrooms, each with windows on two sides, became a standard for California K-12 campuses.

However, starting in the late 1960's a number of forces came into conflict with the daylit design of classrooms. Engineers, asked to provide air conditioning in classrooms, argued against the use of large expanses of glass and high ceilings. Construction economists argued that schools could be built less expensively on smaller sites if the classrooms could be built back to back or grouped together, without constraints on solar orientation. Educational theorists argued that a more flexible arrangement of classrooms, with open walls between them, would encourage team teaching and creative learning. And educational planners, trying to meet the needs of an exploding school age population, required that at least one-third of all new classrooms be portable, so that, if the need arose, they could be moved to new areas with an overpopulation of students.

As a result of these pressures, the finger plan school was largely abandoned in California, and a vast experimentation in school design began. Many of the classrooms built since the 1960's have little daylighting. Windows are commonly built with "black glass" (T_{vis} 19%) that allows a view out, but no useful daylight in. Numerous schools have been built with no windows at all. Similar trends occurred nationally and internationally.

Recently, some informal studies in the United States claiming a relationship between daylighting and enhanced student performance have generated considerable excitement among daylighting advocates.[2] These studies, along with a rising interest in "natural" and "healthy" environments, have contributed to a resurgent interest in daylighting in schools.

Daylighting has the potential to either positively or negatively impact the energy performance of schools. Designed poorly, and implemented without photocontrols to reduce the use of electric lights, daylight designs can raise both heating and cooling requirements for schools. Implemented well, with careful selection of glazing systems, orientation and automatic lighting controls, daylit schools can substantially reduce peak electricity demands and HVAC loads (Arasteh, D. et al 1985).

The School Data

We obtained student performance data from three elementary school districts and looked for a correlation between test scores and 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, if the physical

[2] (Nickas, M. and Bailey, G., 1997) The study reports positive results for children moving to daylit schools. However, the analysis does not provide any certainty that this was not a random effect.

environment does indeed have an effect on student performance, it would be most apparent in populations of elementary school students.

We sought out large school districts that had a wide variety of daylighting conditions in their classrooms, and ideally, included a substantial number of top-lit classrooms. Top lighting (from skylights or roof-top monitors) was particularly interesting to us as a way to isolate the effect of daylighting per se from all the other characteristics which might be associated with windows, such as view, visual communication, social status, etc.

We ultimately analyzed test score results for over 21,000 students from the three school districts, located in San Juan Capistrano, California; Seattle, Washington; and Fort Collins, Colorado. The districts provided us with a wide variety of test data sets and student demographic characteristics. We used two test scores, reading and math, as the dependent variables for our models.

A second data set was created describing the physical characteristics for each classroom in the three districts. This data allowed us to take into account the age and size of the classroom and school, the type of the classroom, (open, portable or traditional) as well as the presence and size of windows and skylights.

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 three codes on a simple scale indicating the size and tint of its windows (window code: 0= none to 5=most area, least tint), the presence and type of any skylighting (skylight code: yes-no by type), and the overall quality and amount of daylight provided (daylight code: 0=none to 5=excellent).

Analysis and Findings

The study used multivariate linear regression analysis to identify the magnitude and certainty of effects, and to control for other influences on student performance. Four regression models were run for each district: one pair using math scores as the dependant variable, the other pair using reading scores. For each of these two dependent variables, we ran the model twice, once using the combined daylight code, once using the separate window and skylight codes. The four models are thus named: math-daylight, math-window, reading-daylight, and reading-window. We hypothesized that a robust daylight effect should have consistent effects in all four models, and that by using the four models we might be able to distinguish between a holistic effect of windows, compared to a more specific effect of the daylight from skylights.

With the Capistrano data, we created a model based on the change in test scores between the fall of 1997 and spring of 1998. Thus, this analysis looks at the rate of learning during the school year that the students occupied a given physical environment. The Capistrano District provided by far the most complete and complex data set that we analyzed. We had the most information about its diversity in student population, administrative structure, and physical conditions. In the Capistrano analysis we were also able to account for the influence of the individual school, and to test for the influence of the individual classroom environment. Thus, we have the highest confidence in the results from the Capistrano study.

For the other two districts we had to use only the final spring test scores, rather than the difference between a fall and spring test. While test scores from the previous years were available, there had been too many changes between the two years, in both the student body and the data collection procedures, to make a reliable comparison between years. Thus, the models for these two districts report on a snapshot of student performance at one point in time. There is an assumption that the most recent classroom experience will influence how students perform on tests. However, the absolute level of student performance is a function of many influences, including where each student started at the beginning of the year and all the advantages or disadvantages that the students brought with them into the classroom. Thus, in these models, the demographic and socio-economic variables become important predictors of absolute student performance, and add many more control variables to our final equation.

Capistrano Characteristics

The Capistrano Unified School District, in Orange County, CA, serves a population of more than 40,000 students in 44 schools from kindergarten through high school. It covers more than 195 square miles and includes 10 small cities in an area of southern California that extends 25 miles inland from the Pacific coast. We were provided with data on the district's 27 elementary schools, of which nine included skylights in their classrooms.

The district tends to have a wealthy population, although there are pockets of lower income and immigrant families. The older neighborhoods nearest the coast tend to have the highest average household income. However, new developments farther inland are also very upscale. The district population is 75% white, 17% Hispanic, 5% Asian, 2% African American and 1% other minorities.

School Characteristics

The physical plant of the Capistrano Unified School district is similar in many ways to other California school districts. They have a set of schools which date from the 1950s through the 1990's, with substantially more built in later years. The schools are all single story, and almost all classrooms have a door directly to the outdoors. The district has a number of schools, which represent plan types popular in each decade:

> **Finger schools** from the 50's and 60's with ample daylighting from windows on two sides of the classrooms, grassy planted areas in between the wings, and careful attention to orientation and sun angles.
>
> **Wing schools**, from the late 60's and early 70's with wings of back-to-back classrooms each with a single window wall, usually with very low transmission ("black") glass. Plans generally show little attention to orientation and sun angles.
>
> **Open plan schools** from the 70s, with few, if any, windows into the classroom "pods." Classroom areas were designed to flow into one another, often with a shared central resource area. Partitions have since been added to all of the original open plan schools so that there is some visual privacy, but rarely acoustic privacy, between classrooms. Due to recent class size reduction mandates in California, these open plan schools have often been subdivided into even smaller classroom areas than originally anticipated, creating a maze-like atmosphere.

Modular plan schools from the 80s, typically in wings, but often with clustered classrooms divided by movable partitions and shared work rooms. Built with pre-fabricated elements.

Most recent schools in the 90's have a variety of plan types, some wing schools, some with interior hallways and common workrooms.

Portable or "re-locatable" classrooms. California schools have been required to install portable classrooms to address the needs of a rapidly changing population. These classrooms are similar to mobile homes: they are factory built, shipped to the site, and installed above grade. These portables exist at every school site in the district, and constituted 40% of all classrooms in our data set. Because every school site had at least a handful of portables, and because of their uniformity across schools, the portables served as a standardized element in our analysis.

Figure 1: Classrooms with Maximum (left) and Minimum (right) Daylighting in Capistrano

As described above, the district has a wide range of window conditions, depending on the plan type. In addition to these common school plan types, Capistrano had a rather unique feature, in that many of the later school plans included skylights in the classrooms. In the late 70's, after having built a number of open plan schools with no windows at all, the school board became concerned that natural daylight was essential for a healthy and positive classroom setting, and so directed all architects hired to design new campuses to provide natural lighting in the classrooms, including both windows and skylights. As a result, the district now has nine elementary campuses that include skylights in the classrooms.

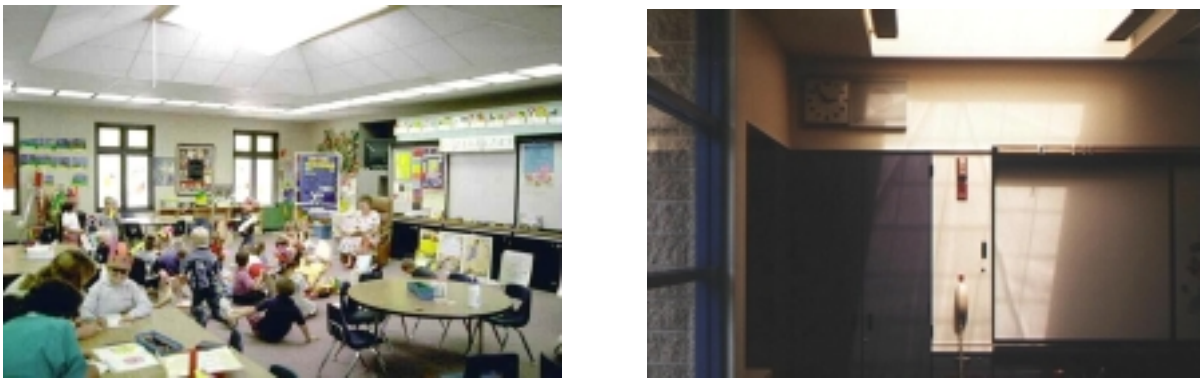

Figure 2: Type A Skylight (left) and Type B Skylight (right)

There are five types of skylights that have been employed in nine of the schools. Two have a diffusing lens that spreads the daylight evenly throughout the classroom (such as Type A skylight in figure 2 above), while three allow patches of sunlight to enter the classroom (type B, above). 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 have no controls at all. The skylights were identified by type in this study, rather than by the amount of daylight they were expected to allow in.

We also collected and analyzed information about the presence of air conditioning and operable windows in the classroom. This was important because most skylit classrooms also had air conditioning, and most classrooms with large window areas also had operable windows. Fortunately, there was enough variety among the various combinations of these conditions to statistically distinguish their effects.

We would have liked to include information about the different types of electrical lighting used in the schools, but this information was not available. Capistrano schools use linear fluorescent lighting throughout the district, and lighting systems are consistently designed to provide an average of 50 footcandles of light on classroom work surfaces. However, there have been so many remodels and retrofits of the electric lighting system in recent years that the actual equipment types—i.e. luminaire, lamp, and ballast types—are highly variable. To create a reliable data set of lighting equipment would have required an on-site audit of every classroom, which was beyond our budget.

Capistrano Results

Figure 3 summarizes the increases in test scores for the daylighting-related variables for the four Capistrano regression models. These models simultaneously controlled for the effect of about fifty other specific variables (HMG 1999a). As part of the analysis we calculated the statistical certainty that these effects were a “true” effect which could be replicated in other analyses of the data. This is expressed as a percent certainty. The chart shows the value of each variable’s effect, its statistical certainty, and the relative effect of each variable compared to the average progress of all students in the Capistrano District.

Capistrano	Analysis Results				Percentage Effect	
NEA	Difference in Average		Statistical Certainty		Difference as a a % of	
Core Level tests	Test Improvement				District Average	
Range: -29 to +79	(normalized RIT points)				Improvement	
Change, Fall to Spring	Reading	Math	Reading	Math	Reading	Math
Combined Daylight Model						
Daylight, Min. to Max.	2.8	2.3	99.9%	99.9%	26%	20%
Operable Windows	0.8	-	99.8%	n/s	7%	-
Separate Skylight and Window Model						
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 3: Summary Daylight Findings for Capistrano

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[3]. 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.

Daylighting was found to have a considerable effect in the Capistrano schools. For example, all other things being equal, students in classrooms with Skylight Type A were found to progress an additional 2 points in reading and 2.3 points in math[4] than those in classrooms without skylights. This translates into a 19% faster learning rate for reading and a 20% faster learning rate for math on average for the children in those classrooms.

Summary results in the Capistrano Unified School District:

The classrooms with the most amount of daylighting are seen to be associated with a 20% to 26% faster learning rate, as evidenced by increased student test scores over one school year, compared to classrooms with the least amount of daylighting.

The classrooms with the most window area are seen to be associated with 15% to 23% faster rate of improvement over a one year period when compared to classrooms with the least amount of windows.

The classrooms with the Skylight Type A are seen to be associated with a 19% to 20% faster improvement when compared to classrooms with no skylights.

The classrooms with the Skylight Type B are seen to be associated with a 21% decrease for reading tests, and no significant results for math tests, when compared to classrooms with no skylights.

Classrooms with operable windows are seen to be associated with 7% to 8% faster improvement in three out of four cases, when compared to classrooms with fixed windows.

[3] 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 this average from our data set.

[4] These are the normalized RIT values. Raw RIT values are 1.7 and 2.6 respectively. Thus, a 1.7 difference in reading scores, divided by the 8.8 district average, equals a 19% effect.

Another way to look at these results is that the average child in the Capistrano district is making about 1 point of progress per month on the reading test and 1.5 points of progress per month on the math test over the course of the approximately eight months between the fall and the spring tests. Students in the most daylit classrooms are progressing more quickly, gaining one to two points more over the course of the school year than students advancing at the average rate. Thus, by advancing more quickly, students in daylit classrooms could save up to one month of instruction time in the reading and math curriculum that could be used for other areas of learning. This was also the same magnitude of effect that could be attributed to attending the highest performing school in the district.

Validity of the Model

The Capistrano analysis was put through two additional statistical tests to determine the validity of the results. One test looked at the "explanatory power" of the daylight variables relative to the other variables included in the model. The daylight and window variables were relatively powerful when compared to the other variables, while the skylight and operable window variables tended to have lower explanatory power. However, in general, all the daylighting variables offered as good, if not a better, explanation for a student's rate of learning as the variables for which school they attended, whether they were in a special language program, or how many absences they each had.

The second statistical test ran the same data through a new model that looked at the average performance of each classroom group, rather than of individual students. The daylighting variables all remained highly significant in this test. This test implied that the influence of being in a given classroom group, whether because of the teacher or the class dynamics, was less significant than the variations between individual students. This may be because the Capistrano District does not group students into classrooms by abilities, or because the Capistrano teachers are all reasonably similar in their ability to teach the math and reading curriculum. However this statistical test did allay concerns that we had picked up a "teacher effect" instead of a "daylighting effect" in our analysis[5].

The Other Districts

We performed a similar analysis for two other school districts, one for 60 elementary schools in Seattle and another for 21 schools in Fort Collins, Colorado. Due to limitations in the data, the analysis for these two districts was less detailed than for Capistrano.

The studies in Seattle and Fort Collins 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. As a result, more variables show up as significant in the models. For example, students' ethnic background and socio-economic status become important predictors of their actual test scores, whereas in Capistrano these variables were not significant predictors of how far a student would progress in one year.

We have less confidence in the results of these models, since the analysis was less detailed. There is more probability that there are other factors that we were not able to account for that could invalidate the results. However, we find it very suggestive that in two very different districts, in different states, we found very similar results to the Capistrano

[5] A follow up study is planned to see if there is any correlation between daylighting and teacher experience, such that "better" teachers may be more likely to be assigned a daylit classroom. Results should be available by the end of this year.

analysis. In both of these districts we also found large, positive, and highly significant effects for daylighting.

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. However, we are still trying to compare "apples and oranges", so we must generalize and talk about "fruit" instead. The percentage effect is perhaps the best way to compare across districts.

Seattle	**Analysis Results**				**Percentage Effect**	
ITBS	Difference in		Statistical		Difference as a a % of	
Iowa Test of basic Skills	Average Test Scores		Certainty		District Average	
NCE Scale 1-99	(NCE percentage points)				Score	
Spring Scores	Reading	Math	Reading	Math	Reading	Math
Combined Daylight Model						
Daylight, Min. to Max.	7.5	5.6	99.9%	99.9%	13%	9%
Separate Skylight and Window Model						
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 4: Summary Daylight Findings for Seattle

Figure 4 summarizes the percentage effects for the daylighting related variables of the four Seattle models. All these variables were found to have 99% certainty. All other things being equal, students in classrooms with the largest window area, or the most daylight, were found to be testing 9% to 15% higher than those students in classrooms with the least window area or daylighting. A 6% to 7% effect is observed for skylit classrooms.

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

Figure 5: Summary Daylight Findings for Fort Collins

The Fort Collins results in **Figure 5** show a 7% improvement in test scores in those classrooms with the most daylighting, and a 14% to 18% improvement for those students in the classrooms with the largest window areas. There is a 3% 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, which 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 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. Because of this limited range of window conditions in our model, the effect of going from minimum to maximum window area may be underreported.

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

The results for the daylighting variable in Fort Collins are probably also depressed for the same reason, since the daylighting code was partially a function of the skylighting code. We assigned the classrooms with monitors 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. Such observations, however, were beyond the resources of this study.

Discussion and Conclusions

The results of the analyses of the three districts are remarkably consistent: all show positive daylight effects with highly significant results. The actual magnitude of the effects is less important than the observation that a consistent effect can be found in three very different school districts.

We began this study uncertain that we would be able to find any significant effects of daylighting using the statistical analysis methodology. We pursued the study of three school districts in the hope that at least one district would be amenable to this analysis technique.

From this study, we have made a number of important findings:

- We found a uniformly positive and statistically significant correlation between the presence of daylighting and better student test scores in all three districts.
- We found that the positive effect of daylighting was distinct from all the other attributes of windows.
- We found that this methodology of using large, pre-existing data sets can be a successful and powerful tool for investigating the effects of the physical environment on human performance.

There are many other lesser findings that can also be derived from this study. We refer the reader to the more detailed report for full discussion (HMG 1999b)

This type of statistical study has many limitations. It cannot prove the "cause" for an effect. It merely shows the magnitude of an effect and the statistical certainty of an

association between variables. The bottom line is that daylighting has a very strong positive association with improved performance.

Further research is needed to identify the mechanism(s), which produce the effect, and to understand the significant factors in greater detail. Is it the size of the window, the tint, the view or the level of illumination? Is it the spatial or temporal variability of daylight, the spectrum of daylight, or the absence of flicker? Ultimately, such information is needed to help building owners and the designers make informed decisions for future building projects involving both new construction and renovation.

Acknowledgments

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