Windows and Classrooms:
Student Performance and the Indoor Environment

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ABSTRACT

This study investigates whether daylight and other aspects of the indoor environment in elementary classrooms have an effect on student learning, as measured by improvement on standardized math and reading tests over an academic year. The study uses regression analysis to compare the performance of over 8000 3rd through 6th grade students in 450 classrooms in the Fresno Unified School District, CA.

A statistical analysis was conducted in which traditional education explanatory variables, such as student and teacher demographic characteristics, were controlled for. Numerous other physical attributes of the classroom and the indoor environment are also considered as potential influences. In addition to the statistical analysis, 40 classrooms were observed during normal operation and over 100 teachers were surveyed on their classroom operating experience and preferences.

Variables describing a better view out of windows are found to be positively and significantly associated with better student learning, while variables describing window glare, sun penetration and lack of visual control are associated with negative performance. In addition, attributes of classrooms associated with acoustic conditions and air quality issues are also significant. The findings are discussed relative to a previous study at San Juan Capistrano that found that more daylight improved students' performance. The results emphasize the statistical value of working with very large data sets, and of studying the interactions between environmental variables.

Background

This study is the third in a series of studies looking at the relationship between daylighting and student performance. The first, Daylighting in Schools [HMG 2000], examined school districts in three states, and found a positive association of more daylight with better student performance in all three. A detailed reanalysis of the results in one district [HMG 2002] showed a central tendency of a 21% improvement in test scores was found for the students in the most daylit classrooms compared to those with no daylight.

The current study had two primary goals: first, to examine another school district, one with a different climate and different curricula, to see whether the original methodology and findings would hold; and second, to investigate classroom environmental conditions in more detail (especially daylight conditions), to determine which attributes are more likely to contribute to a "daylight effect," if any. Furthermore, understanding daylight interactions with thermal comfort, ventilation, acoustics and view was a further goal of this study.

To achieve as much statistical power as possible, and to ensure continuity with previous studies, the school district selected for this study had to comply with many criteria, including the following: 1.) Use the same standardized tests that were used in Capistrano School District in the previous study, and have previous years' experience with these tests 2.) Have a large student population 3.) Have a different climate, demographic and architectural conditions from those in Capistrano 4.) Contain schools with a wide range of daylight conditions and architectural styles 5.) Avoid confounding factors, such as a strong relationship between school daylight levels and neighborhood socioeconomics. In selecting our study site, we first verified that there was sufficient diversity in our study sample, and also later controlled for these potentially confounding variables in the analysis.

Fresno Unified School District, selected for the study, is the fourth largest school district in California, with 61 elementary schools and 46,000 K-6 elementary students. The population is ethnically very diverse; native English speakers make up only 56% of the elementary school population, with 32% classified as learning English. The elementary school population is classified as 17% white, 56% Hispanic, 12 % African American, 15% Asian and 2% other. Of these, 73% are classified as economically disadvantaged and 10% as Special Education students. Students in grades 3-6 typically ranked in the 30^{th}-36^{th} percentile in state standardized reading tests, and in the 38^{th}-50^{th} percentile in math tests. Fresno is located at the southern end of California's Central Valley that has long, hot dry summers with uninterrupted blue skies; winters are brief, wet and mild, with temperatures seldom dropping below freezing.

School and Classroom Types in Fresno School District

Most permanent school buildings date from the 1950s through the mid-1970s. In the 1950's and 60's elementary schools were planned for daylit classroom, featuring the "finger plan" with long rows of classrooms with windows on two sides. Later educational policy encouraged the development of "open plan" or "pod" schools that featured clustered, interconnecting classrooms, and/or shared multi-purpose spaces. These open plan schools typically had small windows on only one side of the classroom. All classrooms include some form of air conditioning. It is original in all classrooms built since the 1970s and retrofitted in earlier buildings.

For this study, six basic classroom types have been defined, to capture the key differences in layout and daylight availability. These types are shown in Figure 1 through Figure 6, and are described briefly in their captions.

Figure 1. Finger Plan: Classroom with Exterior Entrances, and Large Windows on Two Sides, North and South

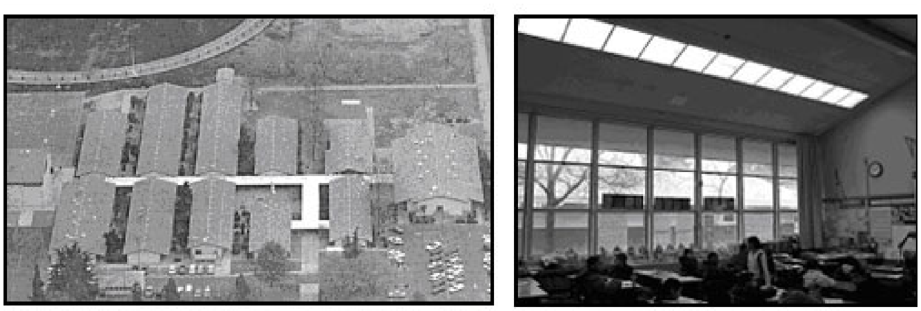


Figure 2. Double Loaded: Wings of Back-To-Back Classrooms with Exterior Entrances, And Large Windows on One Side, Typically North or South

Figure 3. Grouped Plan: Classrooms with an Interior Corridor Often Open to One Another, Moderate Windows on One Side Facing Any Direction

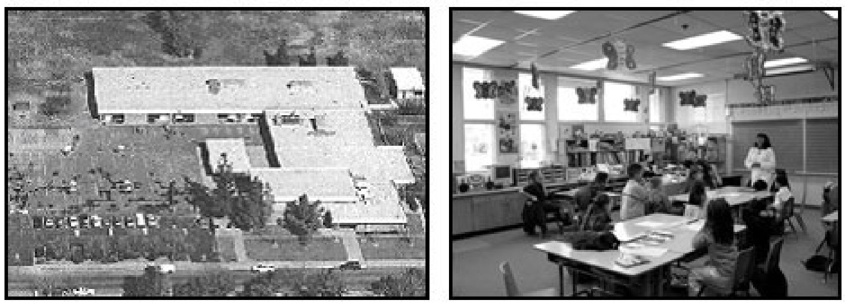


Figure 4. Pinwheel: A Variation of Grouped Plan with Radiating Classroom Wings, With Very Small Tinted Windows

Figure 5. Pod: Non-Orthogonal Grouped Classrooms, with Many Shared Internal Spaces, with Very Small Tinted Windows

Figure 6. Portables: 24' x 40' Modular Classrooms with Exterior Entrances, Typically Lined Up in North or South Facing Rows, With 4' X 8' Windows on Both Narrow Ends

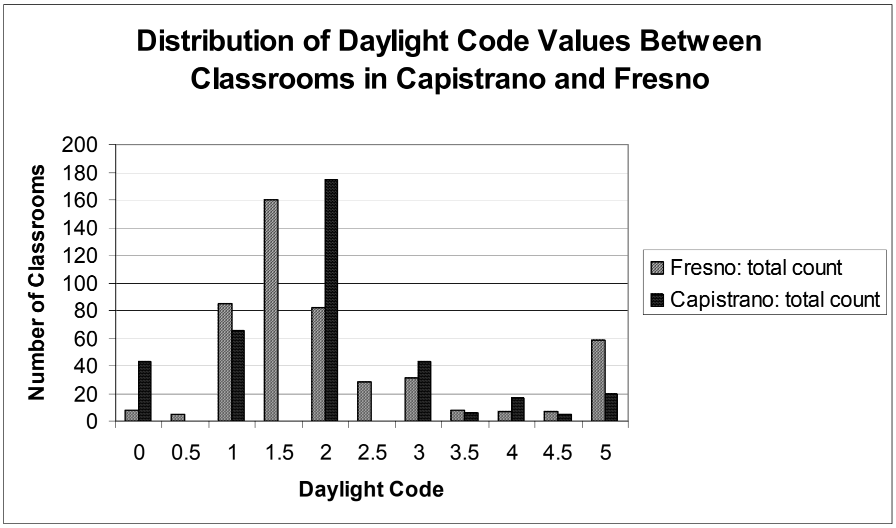
The Daylight Code

The previous studies used a holistic variable called the Daylight Code to rate the amount and quality of light available in each classroom throughout the school year. The Daylight Code was based on a qualitative expert judgment made according to the criteria in Figure 7. Fresno schools contained no skylights. In order to increase the sensitivity of the analysis, and given the greater detail of information about each classroom, Fresno classrooms were categorized in half-code bins, instead of full-bin codes as in Capistrano. The relative distribution of daylight codes in the two studies is show in Figure 8. The majority of classrooms categorized Daylight Code 2 in Capistrano were portables, and in Fresno most categorized Daylight Code 1-3 were portables. Overall, 54% of the Fresno dataset were portable classrooms. The largest group of traditional classrooms fell into Daylight Code 1 (16%) and the next largest group were in Daylight Code 5 (13%), with fewer than 5% in each of the other possible groups.

Figure 7. The "Daylight Code" Used to Assess Daylight Quality in Classrooms

Daylight Code 5	Even and balanced daylight allowing operation of the classroom without any electric lights for a large portion of the school year, resulting in a potential for 45% to 75% annual electric lighting savings.
Daylight Code 4	More asymmetrical daylighting allowing operation of the classroom without any electric lights occasionally, or frequently in just a portion of the classroom, resulting in a potential for 20% to 40% annual electric lighting savings.
Daylight Code 3	Daylight in part of the classroom, which would allow occasional turning off of a portion of the electric lighting, resulting in a potential for 5% to15% annual electric lighting savings.
Daylight Code 2	Some daylight in the classroom, but insufficient for normal operation without electric lights
Daylight Code 1	Minimal daylight
Daylight Code 0	No daylight in classroom

Figure 8. Distribution of Daylight Code Values in Fresno and Capistrano School Districts



Collection of Environmental Information

Much more detailed environmental information was collected in this study than in the two previous studies. 500 classrooms potentially to be included in the study were visited by a survey team for approximately 20 to 30 minutes during the month of August, when the classrooms were not occupied. The team took measurements, photographs, and filled out a four page survey form. This measured and observed information was processed into a variety of environmental variables for consideration in the statistical models. These are briefly listed below, grouped by six "themes" for clarity:

School site characteristics. Age of school, student population, location (near freeway or airport flight path, near agriculture, near boulevard, or near construction site), neighborhood type (residential, commercial, industrial), neighborhood vintage, neighborhood economic status (lower, mid or affluent), school maintenance condition (paint, playground, yard, trees).

Window and daylight characteristics. Area of view window between desk and top of door, area of window above door, window tint(s), window orientation(s), sun penetration (from "never" to "major problem"), glare on teaching wall from windows (never, possible, very likely, major problem), window view (none, mid, far), presence of vegetation or human activity in view, security measures on windows (bars, mesh, Lexan), presence of blinds or curtains, operable area, number of exterior doors, daylight illumination at eight points in classroom at time of survey.

Classroom characteristics. Classroom size (square feet), height, classroom type (seven types, including portables), teaching board type (black, white or green board), amenities (sink, built-in storage, internal bathroom, phone), equipment (TV, aquarium or pet cages), number of computers.

Indoor air quality. Floor type (slab on grade, wood at grade, raised wood, second floor), room indoor air condition (stale air, musty/moldy air, water damage, rodents observed under portables, new condition in classrooms), type of HVAC system, type of HVAC controls, teacher control of fan, presence of portable fan.

Noise. Ballast hum, noisy HVAC system, percentage acoustic wall surface in classroom, percentage of floor covered with carpet.

Electric light. Luminaire type (direct, indirect, direct/indirect, other), luminaire condition, ballast type (electronic or magnetic), lamp color (<3500 ºK, 3500 ºK, >3500 ºK, mixed), control options, horizontal electric light illuminance at three points, lamp type (T8 or T12).

Statistical Analysis

For this paper, the account of the statistical investigation has been abridged; the investigation process is detailed in the full report [HMG 2003a]. The analysis used stepwise linear regression and the dependent variable was the one-year difference in test scores for individual students. The students' previous test scores were included as an explanatory variable. All variables were examined for heteroskedacity and colinearity, and refined as appropriate. The analysis used a significance threshold of $p \leq 0.10$ as the criterion for inclusion of explanatory variables in the models, meaning that for a variable to be found significant in determining tests performance there must be no greater than a 10% chance that this finding was due to chance alone. Of the 150 variables measured, around 70 were found to be significant. This paper reports on the findings from three steps in the analysis: the base model, the replication model and the final model.

As a first step in our analysis, a statistical model with just demographic factors, called the "base demographic model" was developed. This stable model was then used as the basis against which the influence of environmental factors could be judged. The replication model sought to apply the method used in the earlier Capistrano analysis to the new Fresno data. It used a limited set of explanatory variables, similar to those used in the Capistrano models. Next a series of intermediate thematic group models were used to investigate the relationships of the environmental variables listed above. Each group was analyzed on its own and in combination with other groups to identify collinearities and interactions between physical and demographic variables. Collinear variables were redefined or combined to simplify the models. As a last step, the final statistical models considered all environmental variables as they were finally defined along with the base demographic model.

Demographic Model

The base demographic model was less successful at accounting for the variation in student performance in Fresno than it had been in Capistrano. The model R^2 values for the demographic variables explain only 15% of the variation in math scores and 23% of the variation in reading scores. This compares with 34% and 36% respectively for equivalent Capistrano models. It can be concluded that there is more inherent variation in the test scores of the Fresno students than of the Capistrano students. In addition to this inherent variation in the Fresno student population, it is believed that this greater variation in the data is also due to district policies that allow each teacher and school site greater latitude in selecting teaching methodologies and scheduling curriculum material. With more “noise” in the data, a “signal” from environmental effects may thus be harder to find in the Fresno student population.

Replication Model

In the replication model, the Daylight Code was **not** significant in predicting student performance for Fresno, as it had been in Capistrano, Seattle and Fort Collins. Indeed, the Daylight Code had the least explanatory power of the set of variables considered, and the lowest significance level. Thus, the Daylight Code was not found a useful predictor of student performance in the Fresno District, when considering only those variables that were included in the Capistrano model.

The reason for this difference between the two studies became the focus of further analysis. The Capistrano findings might have been overestimated by failing to account for (unknown) confounding variables, or that any relationship between daylight and test scores in Fresno is dependent on different factors that are not well represented by the Daylight Code. We continued our explorations, using the greater detail of data collected at Fresno, to see if more could be learned about the relationship between student performance and the classroom environment.

Final Statistical Models

The final models allowed all environmental variables to compete for significance in explaining student performance on math and reading tests. A very large number of variables were found to be significant, forming very complicated models. However, in general the direction of the predicted effect for each variable seems plausible, given our understanding of the district conditions.

To facilitate interpretation, the findings of the two models, math and reading, are presented twice: once as percentage effects, ordered by the thematic type of variable, and a second time with the variable precision (partial R^2 of the variable), in the order of entry into the model. The percentage effect, shown in Figure 9 and Figure 10, shows how much a student's test score would be predicted to change, on average, if that variable were changed over the range shown. The percentage effect is calculated using the B-coefficient multiplied by a specified range for that variable, and then divided by the mean of the outcome variable. Consistency in performance across models is considered one of the best indicators of a reliable variable. The final column in each table indicates if the significance and direction of the variable were the same for both the math and reading models.

Ten window characteristics enter the one or both of the final models as highly significant; some have a positive association with test scores while others have a negative association. It is interesting to note that variables describing a better view out of windows always enter the equations as positive and highly significant, while variables describing glare, sun penetration and lack of visual control always enter the models as negative. This is the exact same pattern that was found in a companion study of office workers [HMG 2003b].

Figure 9. Math Model, Percentage Effects

Variable Description	Range	% Effect		Consistent?
Fall math RIT score	10% above average		-36%	Yes
Re-test for fall math	If yes	39%		Yes
Student Level Variables				
Third grade	If yes		-15%	
Fourth grade	If yes		-31%	Yes
Fifth grade	If yes		-11%	Yes
Percentage attendance	10% increment	9%		Yes
Enrolled in GATE	If yes	37%		Yes
Special Ed student	If yes		-28%	Yes
Student English development	scalar 3 - 6	12%		Yes
Free lunch	If yes		-5%	Yes
Student gender	If yes		-10%	Yes
Ethnic student (Type 12)	If yes		-10%	Yes
Ethnic student (Type 13)	If yes		-17%	Yes
Ethnic student (Type 15)	If yes		-13%	
Ethnic student (Type 16)	If yes	20%		
Teacher Level Variables				
Multi-grade classroom	If yes		-14%	Yes
Annual salary	$ 10,000 more	4%		
Number of years at FUSD	10 years		-3%	
Mentor teacher	If yes	8%		
Pre-tenure teacher	If yes	13%		
School Socio-economic Characteristics				
School English learner (EL)%	10% increment	18%		Reverses
School parent education	Least to best	25%		Yes
School Characteristics				
Age of school in 2000	10 years more		-4%	
Neighborhood is lower economic status	If yes		-13%	
Neighborhood is prewar vintage	If yes	16%		Yes
Neighborhood is 40s/50s vintage	If yes	7%		
Paint condition	Worst to best	7%		
Classroom Characteristics				
Interior corridor classroom	If yes		-30%	
Operable walls classroom	If yes	14%		
White teaching board	If yes	8%		
Computers	10 more	17%		Yes
Security measures on windows	If yes		-9%	Yes
Window Characteristics				
Daylight Code	None to most		-22%	Yes
Primary window wall faces east	If yes		-12%	Yes
Window area above door	100 sf more	7%		
Glare from windows	None to most		-9%	
No blinds or curtains	If yes		-5%	Yes
Vegetation in view	If yes	10%		
Air Quality & HVAC Characteristics				
Pets in classroom	If yes		-21%	
Central HVAC system	If yes		-7%	
Wall mounted heating unit	If yes	5%		
No teacher control of fan	If yes	7%		Yes
Acoustic Characteristics				
Loud HVAC system	If yes		-17%	

Model Summary:	
RMSE	5.81
R^2	19.2%

Figure 10. Reading Model, Percentage Effects

READING MODEL

Variable Description	Range	% Effect		Consistent?
Fall reading RIT score	10% above average		-46%	Yes
Re-test for fall reading	If yes	30%		Yes
Student Level Variables				
Fourth grade	If yes		-13%	Yes
Fifth grade	If yes		-9%	Yes
Percentage attendance	10% increment	4%		Yes
Enrolled in GATE	If yes	16%		Yes
Special Ed student	If yes		-27%	Yes
Student English development	scalar 3 - 6	11%		Yes
Free lunch	If yes		-5%	Yes
Non-standard living situation	If yes		-16%	
Student gender	If yes		-3%	Yes
Ethnic student (Type 12)	If yes		-4%	Yes
Ethnic student (Type 13)	If yes		-11%	Yes
Teacher Level Variables				
Multi-Grade classroom	If yes		-7%	Yes
Socio-economic Characteristics				
School mobility	10% increment	10%		
School English learner	10% increment		-9%	Reverses
School free/reduced lunch	10% increment	3%		
School parent education	Least to best	27%		Yes
School CalWork	10% increment		-7%	
School Characteristics				
Students in school	100 more		-5%	
School near blvd	If yes	6%		
School near construction noise	If yes	13%		
Neighborhood is residential/commercial	If yes	17%		
Neighborhood is upper economic status	If yes	14%		
Neighborhood is prewar vintage	If yes	11%		Yes
Grass condition	Worst to best	13%		
Classroom Characteristics				
Room area	Small to large	7%		
No doors classrooms	If yes		-12%	
Number of computers	10 more	10%		Yes
Security measures on windows	If yes		-8%	Yes
Window Characteristics				
Daylighting Code	None to most		-29%	Yes
Two exterior doors	If yes	10%		
Primary window wall faces east	If yes		-8%	Yes
Primary window wall faces south	If yes		-9%	
Window area desk-door	100 sf more	14%		
No blinds or curtains	If yes		-5%	Yes
Activity in view	If yes	6%		
Air Quality Characteristics				
Water damage visable	If yes		-15%	
Musty/Moldy air in classroom	If yes		-10%	
No teacher control of fan	If yes	10%		Yes
Percentage carpet	0% to 100%	8%		
Electric Light Characteristics				
T8 lamps	If yes	12%		
Lamp color is warm (CCT<3500)	If yes		-16%	
Mixed fluorescent (poor lighting maintenance)	If yes		-6%	
Acoustic Characteristics				
Loud ballast hum	If yes		-19%	

Model Summary:	
RMSE	5.64
R^2	25.5%

Other environmental variables are also of interest, although somewhat less consistent. A shorthand version of possible interpretation for each significant environmental variable is included as the final column in Figure 11 and Figure 12 below, which also show the order of entry and variable partial R^2 for both models. The partial R^2 values in these models are low compared to those that might be found in a simple laboratory experiment, but are typical of field study results in the social sciences where a highly unpredictable outcome variable is affected by a very large number of environmental, social and personal variables. Those variables that enter the model first generally have the greatest predictive power.

Figure 11. Math Model, Order of Entry

Order of Entry	Variable Description	Partial R^2	Pos.	Neg.	Issues	Possible Interpretation
1	Fall math RIT score	0.043		neg		
2	Enrolled in GATE	0.028	pos			
3	Fourth grade	0.015		neg		
4	Re-test for fall math	0.012	pos			
5	School English learner (EL)%	0.010	pos			
6	Special Ed student	0.010		neg		
7	Student gender	0.005		neg		
9	Percentage of attendance	0.003	pos			
10	Multi-grade classroom	0.003		neg		
13	**Primary window wall faces east**	0.003		neg	Glare	Low-angle morning sun causing glare?
14	Ethnic student (Type 13)	0.002		neg		
15	Ethnic student (Type 12)	0.004		neg		
18	Number of computers	0.002	pos			
20	**Security measures on windows**	0.002		neg	View	Bars on windows provide negative view?
21	Age of school in 2000	0.002		neg		
22	Student English development	0.002	pos			
34	Mentor teacher	0.001	pos			
36	Free lunch	0.001		neg		
37	**White teaching board**	0.001	pos		Glare, IAQ	Less glare, less dust from chalk? More use?
38	Fifth grade	0.001		neg		
39	Third grade	0.003		neg		
40	Operable walls classroom	0.001	pos			
41	Neighborhood is 40s/50s vintage	0.001	pos			
42	**Wall mounted heating unit**	0.001	pos		IAQ	More control of temp.? Portables and finger plan?
43	**Loud HVAC system**	0.001		neg	Noise	Makes hearing teacher difficult?
44	**Pets in classroom**	0.001		neg	IAQ	Possible allergies? Teacher type?
45	Pre-tenure teacher	0.001	pos			
46	Annual salary (per $1000)	0.001	pos			
47	Number of years at FUSD	0.001		neg		
48	School parent education	0.001	pos			
49	**Vegetation in view**	0.001	pos		View	View of outside vegetation is relaxing?
50	**Glare from windows**	0.001		neg	Glare	Too much glare on teaching surface?
51	Neighborhood-lower economic status	0.001		neg		
52	Interior corridor classroom	0.001		neg		
53	Neighborhood is prewar vintage	0.001	pos			
54	**No blinds or curtains**	0.000		neg	Glare	Teacher cant prevent glare/distraction from windows?
55	Ethnic student (Type 16)	0.000	pos			
56	**Paint condition, worse to better**	0.000	pos		Site	Better image=more motivation?
57	Ethnic student (Type 15)	0.000		neg		
58	**Daylight Code**	0.000		neg	Daylight	See Phase 2 analysis discussion
59	**Window area above door (high)**	0.001	pos		Daylight	Less glare, but more daylight?
60	**Central HVAC system**	0.000		neg	IAQ	No individual control over thermostat?
61	**No teacher control of fan**	0.001	pos		IAQ	Mechanical ventilation always on?
16-35	18 Outlier Students	0.021				
	Total R^2	**0.192**				

Perhaps the most compelling are variables associated with acoustic conditions in the classrooms, where variables that would indicate an increase in noise are consistently negative, while those associated with a reduction in noise are positive. For example, *noticeable ballast hum* from the lighting system indicates a negative effect and was the first environmental variable to enter the reading model. Similarly, a *loud HVAC fan* was also negative. Increasing the *amount of carpet* (which reduces acoustic reverberation, creating a quieter classroom) is associated with better student performance in reading.

By summing the partial R^2 values for the window characteristics variables, it can be seen that they account for 0.3% to 0.6% of the variation in student test scores. This is about double the value than the 0.1% to 0.3% accounted for in the Capistrano study by the Daylight Code. This implies that, as expected, the more detailed description of window characteristics in this study is somewhat more effective at describing the effects associated with windows than the cruder Daylight Code. The explanatory ability of the environmental variables may seem small, but they are larger than the partial R^2 of some variables typically considered central issues in educational policy such as *percentage attendance* (R^2 = 0.0030 in math, 0.0008 reading), or the *number of students in the school* (R^2 = 0.0003 reading only), or the number of computers (R^2 = 0.0020 math, 0.0007 reading).

Figure 12. Reading Model, Order of Entry

Order of Entry	Variable Description	Partial R^2	Pos.	Neg.	Issues	Possible Interpretation
1	Fall reading RIT score	0.183		neg		
2	School English learner %	0.011		neg		
3	Special Ed student	0.009		neg		
4	Re-test for fall reading	0.007	pos			
5	Enrolled in GATE	0.004	pos			
6	Fourth grade	0.004		neg		
7	Fifth grade	0.004		neg		
8	**School near construction noise**	0.002	pos		Noise, IAQ	Improving neighborhood??
9	**Loud ballast hum**	0.002		neg	Noise	Annoying hum creates distracting noise?
10	Ethnic student (Type 13)	0.002		neg		
16	**Security measures on windows**	0.001		neg	View	Bars on windows provide negative view?
17	**Primary window wall faces south**	0.001		neg	Glare, Heat	Sun on south window causing glare, overheating?
21	Free lunch	0.001	pos			
24	Neighborhood residential & commercial	0.001	pos			
25	Student English development	0.001	pos			
26	Percentage attendance	0.001	pos			
27	Non-standard living situation	0.001		neg		
28	**Daylighting Code**	0.001		neg	Daylight	See Phase 2 analysis discussion
29	**No blinds or curtains**	0.001		neg	Glare	Teacher can't prevent glare/distraction from windows?
30	**Primary window wall faces east**	0.001		neg	Glare	Low-angle morning sun causing glare?
31	Multi-grade classroom	0.001		neg		
32	**Musty/moldy air in classroom**	0.001		neg	IAQ	Likely indicator of poor air quality?
33	School free/reduced lunch %	0.000	pos			
34	Ethnic student (Type 12)	0.000		neg		
35	School near blvd	0.000	pos			
36	**Water damage**	0.000		neg	IAQ	Possible source of poor air quality? Poor maintenance?
37	**View activity**	0.000	pos		View	More stimulating view of people?
38	Student gender	0.000		neg		
39	**Window area desk-door (view area)**	0.000	pos		View	Larger view area?
40	**Mixed florescent or can't tell**	0.000		neg	Lighting	Poor lighting maintenance?
41	**No teacher control of fan**	0.000	pos		IAQ	Mechanical ventilation always on?
42	**No doors classroom (open clsrm)**	0.000		neg	Noise	Room can't be isolated from neighbors' noise?
43	**Grass condition**	0.000	pos		Site	Lush vegetation = better play area? Better image?
44	School mobility	0.000	pos			
45	Number of computers	0.000	pos			
46	Number of students in school	0.000		neg		
47	**Percentage of floor carpet**	0.000	pos		Noise, IAQ	Reduced reverberance? Less dust?
48	School parent education	0.000	pos			
49	School CalWork%	0.000		neg		
50	Neighborhood upper/affluent economic status	0.001	pos			
51	Neighborhood is prewar vintage	0.000	pos			
52	**Two exterior doors**	0.000	pos		IAQ, Daylight	Cross ventilation? Finger plan classroom?
53	**Lamp color is warm (CCT<3500)**	0.000		neg	Lighting	Older lighting system? Poor maintenance?
54	**Room area**	0.000	pos		Room	More room for students and teachers?
55	**T8 lamps**	0.000	pos		Lighting	Newer, better quality lighting system?
11 to 22	8 Outlier Students	0.012				
	Total R^2	**0.255**				

Further Investigations into the *Daylight Code*

In the replication model the Daylight Code was not significant. However, when variables describing window characteristics were added to the model, the Daylight Code emerged as a significant, but negative factor. Each thematic model was tested with and without the Daylight Code; when the Daylight Code was added the effect of the other variables remained essentially the same. This implied that the Daylight Code was capturing some other (negative) effect not included in our list of potential variables, but that was consistently associated with classrooms along the same distribution as the Daylight Code.

To investigate this, the predicted effect of all the window and daylight characteristics of each classroom on test scores was calculated, and this was plotted as a function of each classroom's Daylight Code (see Figure 13 and Figure 14). A straight line fitted through these points is nearly flat and would show no significance, just as in the replication model, but the best polynomial fit in for both the math and reading scores is a line that curves upward towards both ends. These plots show that many of the high Daylight Code classrooms are performing very well, but so, surprisingly, are some of the lowest Daylight Code classrooms. This unexpected result may be due to other unknown factors which cause students to learn better and that are collinear with the low Daylight Code classrooms, or cause students in the medium and high Daylight Code classrooms to perform worse than expected.

Figure 13. Net predicted effect of window and daylight characteristics on test scores for each classroom (math model)

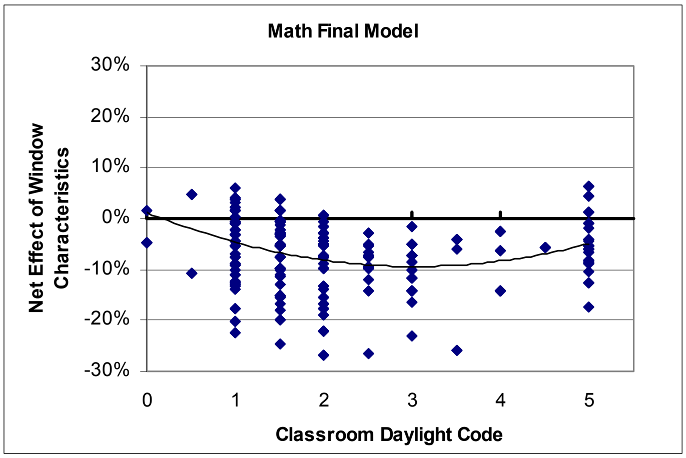
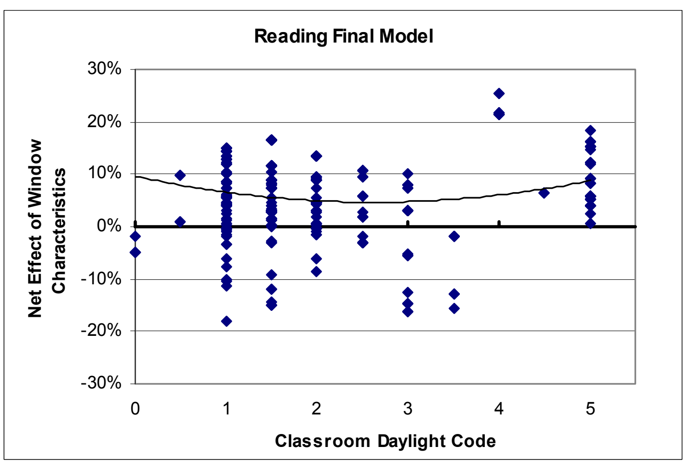


Figure 14. Net Predicted Effect of Window and Daylight Characteristics on Test Scores for Each Classroom (Reading Model)



Several possible explanations for the negative performance of the Daylight Code were carefully investigated during a second phase of the study, when we observed 40 classrooms in operation, and surveyed 100 teachers on their comfort conditions in the classrooms. We considered potential confounding issues such as teachers' use of blinds and curtains, the role of glare and distraction, thermal comfort, ventilation and indoor air quality. But the explanation supported best by our observations is an acoustical one. Acoustic conditions in classroom are likely to be just as important as the visual conditions. Indeed, recent research has revealed that young children actually need noticeably quieter conditions than adults in order to successfully process the same verbal information [Nelson 2003].

During the second phase investigations, we observed the high Daylight Code classrooms tend to have very different acoustical properties to those classrooms with a low Daylight Code. For example, the finger plan classrooms, with high ceilings, large areas of single pane, operable windows and vinyl floors have longer reverberation times, and are also more likely to admit noise from outside the classroom. Open classrooms, on the other hand, with low Daylight Codes tend to have low ceilings, small windows areas with no operable area, and extensive carpeting. Calculations of reverberation time showed that many daylit classrooms in Fresno were likely to exceed the maximum recommended reverberation time [ANSI 2002], whereas classrooms with low Daylight Code values were likely to be better than the recommendation.

In addition to reverberation, there were striking differences in both student and teacher behavior between the two extremes of classrooms. It is common practice in Fresno, with a very high non-English speaking population, to have bi-lingual tutors working with small groups of children simultaneously while the primary teacher instructs the rest of the class. In the high Daylight Code classrooms these tutorials occurred within the reverberant main classroom space, adding distracting voices to the classroom. In the low daylight classroom, tutorials typically occurred in the hallways, or small group spaces adjacent to the classroom, removing the acoustic distraction form the other children.

Furthermore, in the open-plan classrooms surveyors observed that there were surprisingly low ambient noise levels. Teachers explained that students had been trained over the years to use "indoor voices" inside the building, and they rarely had problems with excessive noise from other classes. Based on these observations, we believe that Daylight Code was likely confounded by the acoustic conditions in classrooms. Thus we would recommend that any future investigations also attempt to describe the acoustic performance of classrooms.

The Importance of Window Views

Measures of larger or more interesting views, including view of vegetation, view of human activity, far versus near views, and size of view area were always positive in various models tested. The finding of the importance of view for student performance in Fresno can be considered consistent with the previous school study, where simple window area per classroom was found positive in all three school districts, independent of a "toplighting" effect from skylights or roof monitors. It may be that the mechanisms of view windows and toplighting in influencing student performance are different, and should not be combined in a holistic 'daylight code." This study's view finding is also consistent with the importance of views found in the companion office study [HMG 2003b], where better views were consistently associated with better office worker performance.

These consistent and positive findings would seem to contradict some educational theories that postulate that views can be distracting for students, creating a negative effect on learning. The mechanism for a positive effect for window views can not be determined from this study. But it is interesting that variables describing both size and content of the view were found to be significant. Other researchers have developed theories for such a view mechanism, including increased mental relaxation, increased mental stimulation, and the circadian stimulation from daylight illumination levels received at the eye when looking out a window[1]. To explore the circadian theory in future studies, far more precise measurements of daylight illumination levels should be pursued. This study only measured daylight illumination at the horizontal task plane at one point in time (one day in August, when the classrooms were not occupied). A precise measurement would monitor daylight illumination levels in the vertical plane, as received by the eye of the viewer, as it varies over the course of a day and a year.

Conclusions

While we were not successful in replicating the simple, positive association of the Daylight Code with student performance in this study, we were successful in identifying several characteristics of windows that seem to have consistent associations with student performance, and that are also consistent with other studies. Window characteristics associated with a larger or more interesting view are positive. Window characteristics associated with glare, sun penetration or lack of control are negative. These results show that investments in improving the visual environment in schools can have a measurable benefit in terms of student performance.

A secondary conclusion of this study is that particular environmental effects should not be studied in isolation The human subjects that we are studying are integrating the effects of all indoor environmental conditions—visual comfort, thermal comfort, acoustic comfort, air quality—through their physiological, mental, emotional and behavioral responses. Thus, these aspects of the indoor environment must be studied together. Admittedly, this makes for much more complex studies. However, we have made a first attempt at laying out a methodology that can begin to untangle these various influences on human performance, by using very large data sets, uniform performance metrics and sophisticated statistical analysis.

In the final model, all the physical environmental variables together explain about 1% to 2% of the variation in student test scores. This appears to be a relatively small effect, so why would such an effect be interesting and valuable to know? The small model R^2 values suggest, firstly, that individual student performance is subject to a high degree of variability, influenced by many factors that are not included in this study. Secondly they suggest that the effect of the explanatory variables is not precise, but a rather loose general trend. Thus, the small values of R^2 do not suggest that the effect of explanatory variables is negligible, but rather subtle, requiring large data sets for resolution.

Perhaps the most compelling reason to pay attention to the findings of these models is that the physical conditions of the environment are completely within our control when we make design decisions about new buildings. Furthermore, those design decisions last for the entire life span of the school building or retrofit measure – typically 50 years. Thus, we have a small, but potentially very persistent, opportunity to influence student performance through design decisions[2].

Other studies have shown that the addition of automatic lighting controls that reduce electric light use when daylight is available could also save a good deal of money. If the state encouraged their use in new schools statewide, the savings could accumulate to about $5 to $7 million dollars per year and 3,330 to 4800 megawatt hours of energy savings after ten years of

[1] Please see full report for a discussion of these theories and status of supporting evidence.
[2] In comparison, the class-size reduction program in California spent over $100,000 per classroom affected during its first five years, or more than $100/sf, and achieved no measurable improvement in student scores, per the Rand Corp study commissioned to evaluate the program.

new construction[3]. The energy savings, combined with the positive effects of view out of windows observed in Fresno, or the positive effects of increased daylight observed in Capistrano, create a win-win situation for daylighting design in classrooms.

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