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Indoor Air Quality and Academic Performance

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Abstract

I examine the effect of school indoor air quality (IAQ) on academic outcomes. I utilize a quasi-natural experiment, in which IAQ-renovations were completed at virtually every school in a single Texas school district at different points in time, combined with a panel of student-level data to control for many confounding factors and thereby uncover the causal effect of IAQ-renovations on academic outcomes. Results indicate that performance on standardized tests significantly improves while attendance is unresponsive to improvements in IAQ. Rough calculations suggest that IAQ-renovations may be a more cost-effective way to improve standardized test scores than class size reductions. JEL: I21, Q53

Given the substantial time that children spend in schools over their lifetime and given the purpose of this activity, the school environment is an important environment to better understand. To this end, this paper evaluates the effect of indoor air quality (IAQ) in school buildings on students' standardized test scores and school attendance rates. These relationships have significant implications for both human capital accumulation and children's health and development, yet they have received no attention in the economics literature and have been analyzed elsewhere only with limited success. Combining detailed information on indoor air quality-related renovation projects with student-level administrative data, I find that mold remediation and ventilation improvements significantly improve test scores, but that attendance rates are generally unresponsive to renovations.

The importance of human capital accumulation to individual earnings, productivity, and economic growth is well established.[1] Furthermore, it is not just the quantity

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[1] See, for example, Pierce and Welch (1996).

of schooling that is important for these outcomes, but also the quality of schooling.[2] Because school quality cannot be directly controlled, government policy has sought to indirectly improve quality by devoting more and more resources to a variety of school inputs. As a result, since the 1960s real expenditures per student have more than tripled.[3] Given the importance of school quality and the sizable expenditures on school inputs, there has been significant growth in work investigating the extent to which school inputs do, in fact, affect school quality. While these studies consider a variety of inputs, including class size, teacher characteristics, family characteristics, and peer effects, there is an overwhelming lack of research concerning the physical school environment.[4] This paper suggests that the indoor environment, and in particular indoor air quality, may be an important school input to consider.

There are many reasons why indoor air pollution is an important issue in general and why improving air quality in schools might lead to improved student health and academic performance. First, according to the American Lung Association, the average American spends approximately 90% of their time indoors. Second, due to changes in building materials and household products, the U.S. Environmental Protection Agency (EPA) estimates that concentrations of some pollutants, such as volatile organic compounds (VOCs), are often two to five times greater indoors than outdoors and may be as much as 100 times greater. Third, since the energy crisis in the 1970s, building ventilation rates have decreased in order to conserve energy, which has tended to increase the residence time for indoor pollutants and decrease oxygen levels. This increase in exposure over time has lead the EPA to consistently rank indoor air pollution among the top five environmental health risks.[5]

While indoor air pollution poses a risk to all, the risk is greater for children since their bodies are still developing and they breathe a higher volume of air relative to their body size. After the home, the school environment is where children spend the majority of their time, suggesting that this is an environment in which exposure to harmful pollutants should be minimized. Despite this, many public schools are in disrepair. In 1995, the U.S. General Accounting Office (GAO) published a report on the condition of U.S. schools projecting that $112 billion in repairs and upgrades was needed to improve school facilities to good overall condition (GAO 1995). These

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[2] See, for example, O'Neill (1990), Bishop (1991), Grogger and Eide (1995), Neal and Johnson (1996), and Hanushek and Kimko (2000).

[3] For example, teacher-student ratios have fallen by almost 40%, teachers with at least a masters degree have more than doubled, and the median years of teacher experience has almost doubled (Hanushek (2003)).

[4] Jones and Zimmer (2001) and Cellini, Ferreira and Rothstein (2010) examine school facilities.

[5] While indoor air pollution is a concern in developed countries, it is a much larger issue in developing countries where more than three billion people continue to use high-polluting fuels for cooking and heating. In fact, the World Health Organization estimates that indoor air pollution is responsible for 2.7% of the global burden of disease. Duflo, Greenstone and Hanna (2008) survey the current literature on indoor air pollution in developing countries. The general conclusion is that much more work needs to be done in order to understand the potentially important relationships between indoor air pollution and health, school attendance, and productivity.

repairs and upgrades included renovations to ventilation systems and improvements to indoor air quality. More specifically, 27% of U.S. schools, with almost twelve million attending students, reported having unsatisfactory or very unsatisfactory ventilation and 19% of U.S. schools, with more than eight million attending students, reported having unsatisfactory or very unsatisfactory indoor air quality. Since many harmful indoor pollutants are not easily detectable by occupants, the number of schools with poor IAQ is likely to be much greater.

Unfortunately, studying the effects of school indoor air quality is a difficult task in practice. First, unobservable student and school characteristics that, in part, determine academic outcomes are likely correlated with school indoor air quality. For example, school districts that lack the resources to achieve good IAQ may also lack the resources to attract good students, hire good teachers, or obtain good instructional support. Without controlling for these other factors, one cannot identify a causal relationship between IAQ and academic performance. Indeed, this is a problem suffered by the vast majority of studies in this area.[6] A second and larger obstacle is that a measure of school indoor air quality is needed and such a measure is generally not well-known or maintained by school districts. Furthermore, identification requires that measured IAQ vary over time *and* space if we are to control for unobserved time- and student- or school-effects.

To overcome these obstacles, I utilize a unique quasi-natural experiment. Renovation projects designed *specifically* to improve school IAQ were completed at virtually every elementary school within a single Texas school district at different points in time throughout a five-year period, providing plausibly exogenous cross-sectional and time-series variation in school indoor air quality. Coupling detailed information on these projects with a panel of student-level administrative data for the same time period, I am able to control for many of the confounding variables that may also affect academic outcomes and thereby identify the causal effect of indoor air quality-related renovation projects on academic outcomes. While these data are not without drawbacks, I argue in Section 2 that these are the best currently available for this purpose and that they substantially improve upon previous studies.

I find that performance on standardized tests significantly improves while attendance rates are unresponsive to indoor air quality-related renovations. Specifically, the average mold remediation project (~$500,000) improved math scores by 0.15 standard deviations (sds), improved reading scores by 0.14 sds, and increased the probability of passing the reading test by 4%. The average ventilation improvement project (~$300,000) improved math and reading scores by 0.04 sds and 0.09 sds, respectively, and increased the probability of passing these tests by 1% and 2-3%, respectively, although significance is only achieved for reading. Larger budget projects had even larger and more significant effects on test scores. Given the costs of renovations and the size of the effects, these results suggest that indoor air quality-related renovations are a cost-effective way to improve standardized test scores.

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[6] These studies are discussed in Section 2.

The rest of this paper is organized as follows. Sections 1 and 2 discuss related literature on ambient air pollution and indoor air pollution, respectively. Section 3 describes the details of the renovation projects and student data used in the analyses. Section 4 describes the methodology, Section 5 presents the results, and Section 6 discuss policy implications and concludes.

1 Ambient Air Pollution

Detrimental effects of exposure to *ambient* air pollution on infant mortality and children's health, school attendance, and test performance have been documented. Chay and Greenstone (2003) and Currie and Neidell (2005) focus on infant mortality. The former finds that a reduction in total suspended particulates (TSP) decreases infant mortality and the latter finds that a reduction in carbon monoxide (CO) and, to a lesser extent, particulate matter (PM_{10}) decreases infant mortality. Neidell (2004) looks at child hospitalizations for asthma and finds a strong link between ambient CO concentrations and the number of ER asthma admissions. Currie et al. (2009) focuses on school attendance and finds that high levels of ambient CO significantly increase school absences, although results are inconclusive for ozone and PM_{10}. Sanders (2012) addresses the long term consequences of exposure to ambient pollution and finds a negative effect of *in utero* TSP exposure on future high school test performance. Lavy, Ebenstein and Roth (2012) examine the contemporaneous effect of ambient pollution exposure on academic performance and find that increased exposure to $PM_{2.5}$ and CO significantly decreases scores on high school high-stakes exit exams.

While these studies provide evidence of a link between exposure to air pollution and adverse child outcomes, it is not clear how these results can be applied to the indoor environment. Importantly, there are differences in indoor and outdoor pollutants. Indoor air pollution is not simply a byproduct of outdoor air pollution. Rather, it is largely the result of accumulated emissions from *indoor* sources that are not properly ventilated. For example, typical sources of indoor air pollution include cabinetry and furniture made of pressed wood products that off-gas VOCs like formaldehyde; damp ceiling tiles and carpet that breed mold and other biological contaminants; cleaning products that contain VOCs like hydrocarbons and aldehydes; purported air fresheners that intentionally emit VOCs like terpenes; combustion sources, such as gas heaters, which may leak nitrogen oxides (NO_x); and human occupants that emit carbon dioxide (CO_2) and body odor. These pollutants are not the focus of ambient air pollution studies. Furthermore, given the different mix of pollutants found indoors, indoor chemistry and the resulting chemical byproducts are likely to be very different between the two environments. Moreover, the activities that children participate in are quite different between the indoor school environment and the outdoor environment. While it could be argued that health outcomes may be similar whether exposed to a specific pollutant indoors or outdoors, academic outcomes need not be similar if academic activities take place primarily indoors. And, in any case, there is a lack of evidence connecting contemporaneous exposure to ambient air pollution with academic achievement.[7]

2 Indoor Air Pollution

Exposure to indoor pollutants can lead to a variety of health and cognitive problems, which can affect students' academic performance.[8] More severe health effects include asthma, respiratory infections, skin rash, and fever and are likely to result in school absences. Furthermore, increased absenteeism decreases the quantity of schooling received, which may negatively affect human capital accumulation and result in lower test scores. More mild health effects, such as eye and nose irritation, nausea, fatigue, and dizziness, and cognitive effects, such as difficulty concentrating, impaired memory, and slowed mental processing, are less likely to result in school absences, but may have a direct effect on learning performance and, therefore, human capital accumulation and test performance.

A number of medical and environmental engineering studies have looked at the relationship between exposure to indoor air pollution and student health and performance and, indeed, many find negative associations. However, the vast majority suffer from a lack of sufficient data, resulting in small sample sizes and being unable to convincingly control for potential confounding variables so that causal effects cannot be reliably inferred.[9] Still, several studies that utilize longitudinal data or otherwise have strong designs have found some evidence that improved indoor environmental conditions positively affect student health and academic performance.

Smedje and Norback (2000) find that the installation of new ventilation systems improves school indoor air quality and decreases the prevalence of self-reported asthmatic symptoms. Approximately 1,500 students (1st, 4th, and 7th graders) from 39 schools in Sweden completed a health-related questionnaire in 1993 and again in 1995. Between these dates, new ventilation systems were installed in several of the schools, affecting 10% of questionnaire respondents. Measurements of environmental factors were taken in 100 classrooms in both 1993 and 1995 and in both treated and non-treated classrooms. Comparing measurements across years, results indicate that the increase in ventilation rates and the decrease in humidity and concentrations of CO_2, formaldehyde, other VOCs, respirable dust, and total mold were greater in classrooms with new ventilation systems compared to those left un-treated. Furthermore, while the reporting of asthmatic symptoms increased over time in all schools, it was less pronounced in schools with new ventilation systems.[10]

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[7] As Lavy, Ebenstein and Roth (2012), the exception, notes "evidence documenting a link between cognition and ambient air pollution is extremely limited" (p. 2).

[8] See the EPA's website on indoor air quality: http://www.epa.gov/iaq.

[9] Mendell and Heath (2005) and Daisey, Angell and Apte (2003) offer detailed literature reviews.

[10] Asthmatic symptoms were defined as "recurrent episodes with persistent cough, persistent wheeze, or shortness of breath, or during the past 12 mo had experienced an asthmatic attack,

In a field experiment in Denmark, Wargocki and Wyon (2007*a*,*b*) find evidence that improving classroom ventilation increases the speed at which students perform tasks, but does not affect errors made. The experiment was conducted twice, once in winter and once in summer. In each case, two classrooms, with 10- to 12-year old students, participated in the blind cross-over study for a two-week period. During the first week, outdoor air supply in one classroom was mechanically (and unknowingly to the occupants) increased while it remained unchanged in the other classroom. Conditions were switched in the second week. Throughout both weeks, students were administered identical versions of numerical- and language-based performance tasks. The authors found that the speed with which five of seven of these tasks were performed was generally faster in classrooms with greater outdoor air supply. However, no difference in errors made was observed for any task in either experiment. Bako-Biro et al. (2012) also study the effect of classroom ventilation on the speed and accuracy of tasks performed by school children. The study design is very similar to Wargocki and Wyon (2007*a*,*b*), with the notable exception that twice as many classrooms (eight) were studied. Nine tests were administered to students. The authors found that students' error-free reaction time was lower on four tests when ventilation rates were higher. Differences in error-free reaction time between high and low ventilated classrooms for the remaining five tests are insignificant.

In both experimental studies, students' exposure to better indoor air quality is short-lived (one week). In a cross-sectional study, Haverinen-Shaughnessy, Moschandreas and Shaughnessy (2011) look at a longer period of time by relating classroom ventilation rates with student pass rates on annually-administered state-wide standardized tests in math and reading. One fifth-grade class in each of 104 elementary schools across two school districts in the southwest United States participated in the study. The authors estimated ventilation rates for each classroom and collected test pass rates and average student demographics.[11] Controlling for these demographics, they find that, for classrooms with ventilation rates in the range of 0.9 to 7.1 liters/second (l/s) per person (which are lower than recommended), a 1 l/s per person increase in the ventilation rate is associated with a 2.7% (reading) to 2.9% (math) increase in the number of students passing standardized tests.[12] Identification relies on student demographics adequately controlling for student and school characteristics that affect test pass rates and that are correlated with ventilation rates.

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shortness of breath after exercise or nocturnal shortness of breath" (pg. 27). No significant differences were found in changes of reports of pollen or pet allergies or doctor's diagnosis of asthma between classroom types.

[11] Demographic variables that are controlled for include % free lunch, % limited English, mobility rate, and % gifted enrollment.

[12] The median estimated ventilation rate in these classrooms was 3.6 l/s per person, with a range of 0.9 to 11.74. In their preferred specification, the authors drop thirteen schools with ventilation rates greater than 7.1 l/s per person, which corresponds to the ASHRAE recommended ventilation rate at the time of the study. When these thirteen schools are included, the authors still find a positive association between ventilation and pass rates, but the results are insignificant.

Given the likely correlation of important unobservables with school indoor air quality, to identify the effect of ventilation or other indoor parameters on academic performance it is ideal to have measurements of indoor parameters over time at a number of classrooms or schools (i.e. a panel). Furthermore, it is ideal to have observations over several years, rather than weeks, so that long term outcomes can be analyzed, such as performance on standardized tests which, presumably, assess learning over the academic year. Finally, it is preferable to have objective measures of academic performance, such as test scores and attendance, rather than subjective measures, such as those obtained from questionnaires. To my knowledge, this paper is the first to utilize data that meet all three criteria.

3 Data

3.1 Renovation Projects

In early 2000, severe mold growth was discovered at an elementary school in a Texas school district. While this was remediated, the school board, along with independent indoor air quality experts, inspected the remaining schools in the district for mold and other damage or deficiencies that might deteriorate indoor air quality. Upon finding damage at numerous schools, the school board drafted a $49.3 million bond initiative in the fall of 2001 to fund district-wide renovations. The focus of the bond was to address water intrusion issues and improve ventilation systems at the majority of the schools in the district. The bond was passed in February 2002 with an overwhelming 77% voter approval rate and renovations began during the summer of 2002. The bond proposal, which specified the budget, scope, and timing of renovations at each school, was fixed at the time of voting (February 2002). This ensures that treatment was exogenous to anything that may have occurred after the fall of 2001. Furthermore, school administrators were not given access to bond funds and were not responsible for executing their own renovations. Rather, independent contractors were hired by the school board to complete projects. This ensures that bond funds were used explicitly for indoor air quality related renovations and were not diverted to other activities.

Measurements of indoor pollutants were not taken during the sample period so changes in IAQ are identified simply by the occurrence and timing of renovations. However, differences in project scope and budget allow for a somewhat more refined analysis. The school district provided records of the construction contract award date and substantial completion date of projects at each school as well as project expenditures and a short description of the project scope. Based on these descriptions, projects can be grouped into six categories: crawl space repairs, mold remediation, roof repairs, site drainage enhancements, ventilation improvements, and waterproofing.[13] While the purpose of all projects was to achieve healthy indoor air, variation

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[13] Examples of project descriptions provided by the construction management department are as

in project goals – e.g. improving air quality versus preventing deterioration – will likely result in variation in air quality changes, suggesting that some projects may be more successful at improving academic outcomes than others. For example, the better-designed studies discussed in Section 2 suggest that ventilation improvements lead to better academic outcomes and it was the discovery of mold, specifically, that prompted the school district to draft the bond initiative in the first place. To investigate the possibility of differential effects, in addition to pooling all projects together, each project type is considered separately.

Of the 74 elementary schools in the district, 66 had at least one indoor air quality-related renovation project funded by the bond initiative and the majority had more than one project completed.[14] The latter fact complicates separately identifying project types since, in many instances, projects occurred simultaneously so that the effect of one project type (e.g. mold remediation) cannot be isolated from the effect of any concurrent projects (e.g. roof repairs). In addition, for the eight schools receiving mold remediation, a single construction company was responsible for most or all of the projects competed and only one combined budget for these projects is reported. In these cases, in addition to timing issues, money spent on other projects cannot be controlled for. These complications are addressed in more detail below and should be kept in mind when interpreting results.

Figure 1 illustrates the timing and duration of renovation projects at each of the 65 schools renovated between 2002 and 2007.[15] The x-axis captures time, where "Fa" denotes the beginning of the fall semester, "Sp" denotes the end of the spring semester, and narrow columns represent summer vacations. Each row corresponds to one of the 65 elementary schools that received IAQ-renovations. Schools are ordered and labeled according to total expenditures on renovations, with School 1 receiving the most funding and School 65 receiving the least. For each school, a shaded horizontal bar illustrates the timing and duration of renovations, so that white space indicates periods of time in which no renovations were taking place. For example, renovations began at Schools 2 and 3 during the summer of 2002 and ended midway through the 2002 school year at School 2 and in the summer of 2003 at School 3.

Beginning and end dates are based on the date the construction contract was

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follows: (i) crawl space repairs - "provide/modify mechanical ventilation of under floor crawlspace", (ii) mold remediation – "remove/replace mold contaminated drywall and acoustical ceiling materials"; (iii) roof repairs – "replace metal roof and wall panels and related flashing systems"; (iv) site drainage enhancements – "install underground drainage pipes and divert water away from front of building to improve site drainage"; (v) ventilation improvements – "modify/replace existing [heating, ventilation, and air conditioning (HVAC)] systems and ductwork"; and (vi) waterproofing – "replace waterproofing, damp-proofing and sealant systems".

[14] The eight untreated schools were built in 1998 or 1999 and deemed to have satisfactory indoor air quality in the fall of 2001 when the bond initiative was drafted.

[15] Sixty-six elementary schools received bond-funded IAQ-renovations. However, the school at which mold was first found was renovated during the summer of 2000, which falls outside the date range for which I have data. In addition, renovations at School 1 began in the fall of 2001 due to excessive need. Projects at both schools were funded retroactively by the bond once it passed.

awarded and the date the project was substantially completed, respectively, as designated by the school district's construction management department. Given these definitions, these dates likely overstate the true duration of renovation projects. It was no doubt a goal to limit the disruption from projects by scheduling the majority of work during school vacations and, clearly, projects are concentrated in the summer months. However, many spill over into the school year. These school years can either be classified as "during treatment" or "before/after treatment" depending on how much they are perceived to disrupt the school year. Because project durations are likely overstated and to maximize the number of before/after observations, the results presented below are based on specifications in which school years that have projects ending no later than October 31 are classified as "after" and school years that have projects beginning no earlier than April 1 as "before". If a project is reported ongoing at any point between October 31 and April 1, the school year is classified as "during" treatment. Results are robust to variations in these cutoffs.

Projects are color-coded according to the variety of other projects occurring simultaneously. All projects are first mapped in light gray. Renovations that include ventilation improvements and/or roof repairs, but not mold remediation, are then mapped in medium gray. Finally, projects involving mold remediation are mapped on top of this in black. As can be seen from Figure 1, there is considerable heterogeneity across schools and project types. For example, the timing of renovations varies across project types, which is loosely illustrated by the high concentration of black in the early years, medium grey in the middle years, and light gray in the later years. All mold projects were completed by the beginning of the 2003 school year. Two thirds of ventilation projects were also completed by or during the 2003 school year.[16] Roof projects are split fairly evenly between the summer of 2003 and the summer of 2004. Waterproofing projects occurred throughout the sample, but more than half were completed during the summer of 2004. Finally, site drainage and crawl space projects tend to occur late in the sample period. According to the construction management department, renovations were scheduled according to need, meaning schools with the poorest indoor air quality received renovations early on. This would indicate that mold remediation was necessary to clean up the most polluted schools, followed by ventilation improvements, roof repairs, and so on, and suggests, again, that there may be a differential effect of project type on academic outcomes.

Projects contribute to identifying a treatment effect provided academic outcomes are observed for students both before and after renovations. Unfortunately, the standardized test administered to students changed substantially between the 2001 and 2002 school years and I have only been given access to results from the new test. As a result, I do not observe academic performance "before treatment" for Schools 1 - 5, effectively rendering these control schools. Furthermore, another bond initiative focusing on a broader range of school improvements funded projects that began as

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[16] This, and the following facts, are clear when project types are graphed separately. However, given space constraints, only the combined graph is shown.

early as the fall of 2005 at a few schools and in 2006 at several other schools. To isolate the effect of IAQ-renovations from other types of school improvement projects, all school-year pairs during or after which a non-IAQ project was completed are removed from the sample. This results in dropping projects at nine schools and several "after treatment" periods for several other schools. However, all nine of these schools had additional renovations completed early in the sample, so, while several years are dropped, these schools remain in the sample. For example, two IAQ projects were completed at School 59: roof repairs in the summer of 2004 and site drainage enhancements during the 2005 school year. In addition, a non-IAQ project commenced at the beginning of the 2005 school year. So that the estimated treatment effect is not contaminated by the influence of the latter project, the 2005 and 2006 school years are dropped from the sample for this school. Three school years remain for School 59 where 2002 and 2003 are classified as "before treatment" and 2004 is classified as "after treatment". As another example, non-IAQ projects began at School 64 in the summer of 2006. No IAQ projects are dropped as a result, but only school years 2004 and 2005 are included as "after treatment" periods, while 2006 is removed. Aside from these projects, I am not aware of any other activities or expenditures that varied systematically with the timing of IAQ-renovations.[17]

Figure 2 illustrates budget distributions for each project type separately. Pro-jects are again color-coded according to the variety of other projects occurring simultaneously. In each graph, white indicates projects that do not contribute to identifying a treatment effect. These consist of the nine projects that, as mentioned above, are dropped due to potential contamination resulting from the simultaneity of non-IAQ projects.[18] The remaining shaded projects are "identifiable" in the sense that they contribute to identification of the treatment effect. Light gray represents projects that include mold remediation, which command the largest budgets of all renovations. However, these three schools simultaneously received ventilation, waterproofing, and site drainage improvements and, at each school, one budget was provided for all projects.[19] As a result, it is not possible to identify time and money spent solely on mold remediation so it may be more appropriate to think of mold specifications as identifying the effect of large, full-scale IAQ-renovations on academic outcomes rather than the effect of mold remediation only.

Because time and money spent on mold remediation cannot be isolated from time and money spent on other projects and because a good deal of money was spent at these schools, it is of interest to analyze the effect of other project types in the absence of mold projects to ensure that mold remediation is not solely driving results.

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[17] Such possibilities are discussed in more detail in Section 4.

[18] In theory, projects at Schools 1 - 5 would also be included in this category. However, renovation expenditures at these schools were substantially larger (mean = \$2.5M) than expenditures at the remaining 60 schools. To keep graphs legible – i.e. reduce the range of the x-axis – and because these projects ultimately are not included in the analysis, they are excluded from the distributions.

[19] Two of the three schools also simultaneously received roof repairs, although these projects were billed separately.

These remaining projects are shaded in dark gray. Budget statistics for the differing samples are shown in the upper right corner of each graph. For example, the mean expenditure on ventilation projects across all schools renovated between the spring of 2003 and the fall of 2007 ($N = 18$) was \$341,048. Once unidentifiable and mold projects are removed, the mean drops to \$300,385 ($N = 13$).

A quick glance reveals substantial heterogeneity in project expenditures. Mold and ventilation projects clearly command the greatest expenditures, followed by waterproofing, roof, site drainage, and crawl space projects. While project budget can be, and is, incorporated in the empirical model, it is important to note that all specifications assume that each classroom in each elementary school is equally affected by renovation projects at that school. This assumption is necessary since the data are not refined enough to track renovations or students at the classroom level. However, if this assumption does not hold and students change classrooms from year to year, the estimated treatment effect may be biased towards zero and standard errors may be inflated. This is because test score differentials of students in renovated classrooms – which we expect to be positive – are combined with test score differentials of students in non-renovated classrooms – which we expect to be zero – to form the treatment group. The assumption of uniform post-renovation school indoor air quality is much more likely to hold for large budget projects than for smaller ones, which may have only affected a subset of the classrooms in a school. As such, it may be difficult to identify any treatment effect from, for example, site drainage improvements.

Although measurements of indoor pollutants were not taken before and after renovations by the school district, it is possible to compare schools studied here with other schools in order to determine the extent to which the effects of renovations analyzed here may be replicated elsewhere. One of the most commonly used proxies for indoor air quality is the ventilation rate and one of the most commonly used proxies for ventilation is the indoor concentration of CO_2.[20] Sanders (2008) measures and reports indoor environmental parameters, including classroom CO_2 concentrations, for 79 classrooms in 20 elementary schools in the district studied here.[21] These measurements were taken during the 2000 school year so they give a rough idea of pre-renovation indoor air quality levels. Comparison of CO_2 concentrations measured in Sanders (2008) with those measured in other studies provides an indication of how

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[20] Low ventilation rates are indicative of overall poor indoor air quality. If there are indoor pollution sources, such as mold or VOC-producing products like particle board and air fresheners, low ventilation means these pollutants are remaining indoors for long periods of time and that oxygen levels are low. Conditional on factors such as such as outdoor CO_2 levels, the number, age, and regular activity of classroom occupants, and the time and location of sampling, indoor CO_2 concentrations provide a decent estimate of the air exchange rate or ventilation rate. In addition, while indoor CO_2 concentrations are typically interesting because they correlate well with the prevalence of other indoor pollutants, recent evidence suggests that CO_2, in and of itself, may negatively affect performance (Satish et al. (2012)).

[21] These parameters were measured as part of a civil engineering dissertation aiming to establish baseline indoor characteristics of schools in Texas.

the school district studied here compares to others in terms of indoor air quality.

Figure 3 reports distributions of mean classroom CO_2 concentrations measured in Sanders (2008) and six other studies. In descending order, these studies examine elementary school classrooms in (1) Texas (2) Michigan, (3) Washington and Idaho, (4) Reading, England, (5) Texas, (6) South Carolina, and (7) Uppsala, Sweden. In each study, the mean indoor CO_2 concentration, measured in parts per million (ppm), across all measured classrooms is illustrated by a black dot, one standard deviation above and below the mean by the medium gray region (when available), and the minimum and maximum by the light gray region. The vertical line at 1,000ppm represents the maximum indoor CO_2 concentration recommended by ASHRAE.[22] Concentrations above this are indicative of substandard ventilation rates. Figure 3 indicates that the school district studied here is similar to other schools and that many, even most classrooms have lower than recommended ventilation rates, which is consistent with the U.S. GAO's findings (GAO 1995). This suggests that results from this study may be relevant for many other schools. Furthermore, Smedje and Norback (2000) report an average reduction in indoor CO_2 concentrations of 270ppm in classrooms outfitted with new ventilation systems. Given the average pre-renovation indoor CO_2 concentration of 1,050ppm in their study, this corresponds to a 26% reduction in CO_2. The implications of these findings are that ventilation improvements have the potential to dramatically shift the distributions in Figure 3 leftwards moving many classrooms, including the majority of classrooms studied in Sanders (2008), into the ASHRAE compliant range.

3.2 Student & Teacher Administrative Data

The school district provided administrative data on all students that attended and all teachers that taught at each elementary school within the district at any point between the fall of 2002 and the spring of 2007. Student-level performance data include school attendance rates and scores on the annually state-wide administered Texas Assessment of Knowledge and Skills (TAKS) in math and reading. School attendance rates are recorded for students in grades 1 - 5. However, the TAKS is only administered to grades 3, 4, and 5. Each performance measure provides a different insight into the effects of indoor air quality. While attendance rates serve as a proxy for heath, test scores measure learning, which is presumably affected both by the quantity of learning (measured partly by attendance) and by the quality of learning. Cognitive and mild health effects from indoor air pollution may affect students' quality of learning, thereby affecting test scores, while not inducing them to stay home more frequently. This is supported anecdotally. The imposition of having to make arrangements to keep a child home from school can be substantial. Many parents claim that they will not keep their child home from school unless their child is

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[22] ASHRAE is the American Society of Heating, Refrigerating, & Air-Conditioning Engineers. Among other objectives, they develop standards for the built environment.

particularly sick. This implies that there is likely a "sickness threshold" that must be met before school attendance would be affected. If changes in school air quality are likely to reduce symptoms such as runny nose, itchy eyes, and difficulty concentrating – symptoms that, on average, are not strong enough to induce parents to keep children home from school – this suggests that test scores may be more responsive to changes in indoor air quality than attendance rates.

Student demographic information was also provided and consists of gender, ethnicity, and membership in the following groups: limited English proficiency, gifted, special education, at risk, and economically disadvantaged. Teacher-level data include total and within-district teaching experience and yearly salary and stipend. Each student and teacher is assigned a unique ID so that they may be tracked throughout the sample period as well as paired together in each school year.

4 Method

Two main factors make identifying the effects of school indoor air quality a difficult task in practice. Foremost, a measure of indoor air quality is needed and such a measure is rarely available. I use the occurrence of IAQ renovations, which vary across time, project scope, and expenditure, to proxy for changes in school indoor air quality. Second, to identify causal effects, one must control for student and school characteristics that affect academic outcomes that are also correlated with indoor air quality. For this, I exploit the panel nature of my data to control for time-constant student and school heterogeneity as well as include relevant time-varying factors, which are discussed below.

I estimate variations of the following fixed effects model

$$\begin{aligned} P_{i,s,y} = {} & IAQ_{s,y}\beta + class_{i,s,y}\gamma + teacher_{i,s,y}\theta + year_t \\ & + grade_{i,s,y} + \alpha_{i,s} + u_{i,s,y} \end{aligned} \tag{1}$$

where i, s, and y refer to individuals, schools, and school years, respectively. Depending on the specification, P, performance, denotes either (a) the student's yearly attendance rate, (b) the student's normalized score on the TAKS in math or reading, or (c) whether the student passed the TAKS in math or reading. The vector IAQ includes variables that describe school indoor air quality and is discussed in detail below. The vector *class* includes student *i's* homeroom class size. This is constructed by summing the number of students paired to student $i's$ teacher in school year y. Additional classroom variables are considered in Section 5.3. The vector *teacher* includes the homeroom teacher's years of experience within the district and the teacher's salary.[23] A vector of school year fixed effects, *year*, captures any district-wide time

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[23] I only include homeroom teachers' characteristics because I do not have data on the characteristics of other teachers that students may visit throughout the school day, such as math and reading teachers. However, most elementary school students spend the majority of their day with

trends and a vector of grade fixed effects, *grade*, captures any systematic differences in performance outcomes across grades. Finally, a vector of student-school fixed effects, $\alpha_{i,s}$, is included to control for time-constant student-school heterogeneity.[24]

I estimate (1) using several different sets of *IAQ* variables. Recall that IAQ-renovations can be grouped into one of six categories based on the type of work completed. Given the variation in project scope and their potential differential effects on air quality, it is of interest to separately identify the effect of each project type on academic outcomes. Ideally, one could do this by including separate treatment variables for each of the six project types in one regression. However, because there is substantial overlap of projects at the majority of schools and because the sample of renovated schools is not that large, such specifications appear to ask too much of the data and generally produce insignificant results.[25] Instead, I estimate separate regressions for each project type with the caveat that treatment effects may partially include the effect of other project types. This caveat pertains especially to mold projects. In the discussion that follows, the term "renovations" refers then to a specific project type – e.g. "ventilation" – and each specification described below is replicated for each of the six project types.

As discussed in Section 3.1, I classify each school-school year pair as one of "before", "during", or "after" treatment. While it is reasonable to speculate that academic performance should be better in after-treatment years relative to before-treatment years, how during-treatment performance should compare is unclear. If renovations are disruptive, academic outcomes may worsen during these years. If, however, renovations are primarily completed during summer months in order to limit disruption and the project end dates provided by the construction management department overstate the true completion of projects, then academic outcomes may improve these during these years. Indeed, preliminary specifications that control for during-treatment periods in addition to after-treatment periods produce mixed results of the effect of the former on academic performance. To keep identification clean, in all specifications discussed below, during-treatment years are dropped from the sample.[26]

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their homeroom teachers.

[24] Fixed effects are specific to the student *and* the school attended such that a student that switches schools will have a separate fixed effect for each school attended. I chose this specification because there is not enough school switching among students to be able to separately identify student fixed effects and school fixed effects.

[25] For example, all schools receiving mold remediation also received ventilation, waterproofing, and site drainage work and two of the three also received roof work. Similarly, ten of the sixteen schools receiving ventilation improvements also received roof work and eleven also received waterproofing work. While most specifications that include separate treatment variables in one regression produce insignificant results, some suggest a significant effect of ventilation improvements on test scores that is very similar in magnitude to the results discussed in Section 5.1. Given this consistency, I do not present results from these specifications here.

[26] Very few school years are classified as during-treatment and the inclusion or omission of these during-treatment years has no qualitative effect on results.

The first and most parsimonious specification I consider is $IAQ_{s,y} \equiv \{after_{s,y}\}$, where the dummy variable, $after$, takes the value of 1 if renovations at school s are complete in school year y and takes the value of 0 if renovations have yet to begin. Therefore, $after$ captures the effect of completed renovations on academic outcomes relative to before-treatment years only. This specification treats all IAQ-renovations equally, regardless of the amount of money spent. However, it seems plausible that the greater the expenditure on renovations the greater the improvement in IAQ. To address this possibility, a second and preferred specification I consider is $IAQ_{s,y} \equiv \{after_{s,y},\ after_{s,y} * budget_s\}$, where $budget_s$ accounts for the amount of money spent on renovation projects at school s and is measured in units of \$100,000.[27] This specification allows for a non-linear effect of going from zero expenditures on renovations to positive expenditures combined with a linear budget effect once expenditures are positive and is roughly support by the raw data. Note, the elementary schools studied here are roughly the same size so results are virtually identical whether school budget or budget per student is used.

Both specifications discussed above do not distinguish between the number of years that have passed since renovations were completed. However, the post-renovation time path of academic outcomes may not be constant. There may be a delay in the response or it may diminish as time passes and understanding how the response evolves over time will be important for cost-benefit analyses of renovation projects. Because test scores are only observed for a maximum of three years for each student, I can only distinguish between the effect of one and two years post-renovations. To do so, in a third specification, in addition to *after* and *after*budget*, I also include (i) *2yrs_after*, which takes the value of 1 if renovations at school s are complete in school year $t+1$ and takes the value of 0 otherwise, and (ii) *2yrs_after*budget*. Here, the coefficients on *after* and *after*budget* describe the effect of renovations on academic performance the first year after renovations are complete, while the sum of the coefficients on *after* and *2yrs_after* combined with the sum of the coefficients on *after*budget* and *2yrs_after*budget* describe the effect of renovations the second year after renovations are complete. If the coefficients on *2yrs_after* and *2yrs_after*budget* are not statistically different from zero, the effect of renovations on academic performance is essentially constant across both post-renovation years.

The model described by Equation (1) identifies the causal effect of renovations provided (i) outcomes at schools receiving certain types of remediation (e.g. mold) or sizable funds for renovations were not trending differently from other schools and (ii) no other factors that also affect academic outcomes varied systematically with the timing of renovations. As for the former, school-wide standardized test pass rates are available on the Texas Education Agency's website. A comparison of pass rates from 1996 to 2002 suggests no discernible difference in time trends across different groups of schools. The strength of the latter assumption depends on whether changes in

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[27] Note, $budget_s$ cannot be directly included in (1) because it does not vary across time and so is absorbed by student-school fixed effects.

behavior relevant to academic performance may have accompanied renovations. One possibility is changes in school expenditures. For example, if the school district used the disruption caused by renovations as an opportunity to also improve classroom technology, it would be difficult to distinguish between the effect of renovations and the effect of new technology. However, this does not appear to be the case. Most capital expenditures, including the IAQ renovations studied here, are financed through bond initiatives. While one other bond initiative was passed during the sample period, it affected only a handful of schools in the latter years of the sample and, in any case, these school-year pairs are not included in the analysis.[28] And although the school district is able to fund capital projects with non-bond resources, the Director of the Construction Management Department stated in email correspondence that "during the implementation of [the IAQ bond program], no other significant capital projects, funded from any other District non-bond funded revenue source, were carried out." Annual operating expenditures on items like instruction and extracurricular activities make up the remainder of school expenditures. While these costs can and do vary from year to year, this information is available from the Texas Education Agency and can be directly controlled for in the regression analysis. I do so in Section 5.3 and find no difference in results.

Another possibility is that teachers and students re-sort in response to renovations. For example, if "better" teachers are more able and eager to move to renovated schools than other teachers, students would experience a boost in teaching ability post-renovations. Similarly, if "better" students are more able and eager to switch to renovated schools, a student's peer group might improve post-renovations.[29] First, it is unclear that teachers or students would want to move to renovated schools. The schools that received large scale renovations are the schools that were found to have the unhealthiest indoor air, which may be perceived as unappealing in spite of remediation efforts. Regardless, teachers and students would have to be sufficiently impatient to move to renovated schools knowing their own school would be renovated in the near future, since the purpose of the bond initiative was to achieve healthy indoor air in all schools in the district. Second, I find no evidence of strategic student switching behavior in the raw data. The fraction of students that choose to leave a school in any given year and the composition of these switching students do not appear to be a function of a school's renovation status.

Nevertheless, it is possible to control for such strategic switching behavior. If some teachers are more able to switch schools than others, it is likely a function of district teaching experience and this is already controlled for in Equation (1). Given the availability of student demographics and the pairing of students and teachers in each school year, it is possible to construct classroom composition variables and

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[28] Furthermore, the timing of these non-IAQ renovations does not vary systematically with IAQ-renovations. Refer to Section 3.1 for a discussion of these projects.

[29] Note, given the inclusion of student-school fixed effects, student switching is only problematic if such re-sorting affects a student's peer group which in turn affects academic outcomes.

include these as explanatory variables in Equation (1) in order to control for the effect of student switching. This specification, which is discussed in Section 5.3, produces similar treatment effects.

Given the available controls, that schools appear to be trending similarly prior to receiving renovations, and that renovation funds could not have been diverted to other activities by school administrators, for identification to fail, some academic performance improving event, unrelated to budget, teacher, or peer changes, would have had to systematically occur across schools at the same time as renovations. For example, if school administrators began using school resources more efficiently in a non-observable way as soon as renovations were complete, identification would be jeopardized. Importantly, such events would have had to coincide with the timing of renovations, and it is difficult to explain why this should be the case.

In order to conclude that indoor air quality, specifically, is the driving force behind any changes in academic performance a further assumption must be made, namely that renovations are improving IAQ and that students are responding to these improvements and not to some other facet of renovations, such as improved appearance of the school environment. This assumption is difficult to test.[30] However, a recent study on the value of school facility investments may help distinguish between these possibilities. Cellini, Ferreira and Rothstein (2010) assess the value of facility investment by estimating the effect of school bond issues intended to fund broadly defined capital projects on local house prices using only referenda that narrowly passed or failed so that such investments are arguably exogenous. To determine whether the estimated value stems from an improvement in academic achievement caused by improved school facilities, the authors regress third grade reading and math test scores on bond passage. They find an improvement of 0.067 standard deviations for reading and 0.077 for math the sixth year after the passage of a bond, where the average bond issue in their sample is $6,309 per student.[31] In the sample of students and projects I study here, an average of $409 per student was spent on IAQ renovations.[32]

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[30] Identifying specific mechanisms is difficult in environmental studies of this nature. For example, Currie et al. (2009) study the effect of ambient pollution on school absences. While their estimation strategy allows them to conclude that high levels of ambient CO *cause* school absences, they cannot identify the specific mechanism underlying these results. The mechanism could be physiological – exposure to high CO makes students sick, causing them to stay home from school; it could be behavioral – parents choose to keep their children home from school on high CO days to protect them; or it could be a combination of both.

[31] The effect of bond passage on test scores is generally positive in the first five years after passage, but effects are much smaller and are not statistically significant. The authors argue that effects should not be visible immediately after bond passage given the time it takes to complete capital projects. However, effects are also small and insignificant beyond year six.

[32] This is calculated as the sum of expenditures on all identifiable IAQ projects ($12,351,269) divided by the total number of students attending all schools receiving identifiable IAQ projects (30,201), where "identifiable" is defined in Section 3.1. Alternatively, the average across all IAQ projects included in the bond issue ($49.3M) and all students in the district – elementary, middle, and high – is $644 per student. Note, the IAQ bond issue was rather small and is not indicative

For capital expenditures of this magnitude, Cellini, Ferreira and Rothstein's results suggest a $0.004-0.005$ standard deviation increase in test scores. The extent to which treatment effects associated with IAQ renovations exceed this provides evidence that improved academic outcomes are the result of improved IAQ, specifically, and not some other facet of typical renovations, such as improved lighting.

5 Results

Results are shown in Tables 1 - 6 and Figure 4. Columns report regression results for different treatment classifications. For example, specifications labeled "All" include all project types while specifications labeled "Mold" classify only projects that include mold remediation as treatment. For brevity, only estimates of treatment effects are shown, but all regressions control for class size, teacher within-district experience, teacher salary, year effects, grade effects, and student-school fixed effects. Robust standard errors, clustered by school, are presented in parentheses below point estimates. For easier interpretation, in Tables 2, 4, 5, and 6 combined treatment effects ("TE") are calculated and reported for (i) the mean budget of all projects classified as "treated" in that specification and (ii) the mean budget plus one standard deviation. Corresponding budget statistics can be found in Figure 2. Standard errors for combined treatment effects are reported in parentheses below estimates. For all estimates, statistical significance at the 1% level is denoted with three asterisks, the 5% level with two asterisks, and the 10% level with a single asterisk.

5.1 Test Performance

Tables 1 - 4 and Figure 4 consider the effect of renovations on TAKS scores in math (Panel A) and reading (Panel B). For each subject, TAKS scores are transformed into standardized scores with a mean of zero and variance of one. Therefore, coefficients report changes in test scores in terms of standard deviations of the relevant test score distribution. Results from the parsimonious specification in which a single treatment dummy variable, $after$, is used to capture renovation effects are shown in Table 1. With the exception of crawlspace repairs, all coefficients obtain the predicted sign. However, few are statistically significant. Still, renovations that include mold remediation appear to significantly improve both math and reading scores and ventilation projects appear to improve reading scores. Furthermore, the magnitude of these effects is of practical importance.

To allow for the possibility that greater expenditures lead to greater improvements in IAQ, Table 2 considers a more flexible specification that also includes the interaction term $after * budget$. For the moment, restrict attention to the first column

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of typical bonds in the district. For example, the bond that was issued in the latter years of my sample raised an average of $6,518 per student, a large fraction of which was spent constructing new schools.

for each project type, labelled "All". The coefficient on $after * budget$ is positive and significant for all project types, except for crawl space repairs. Furthermore, for these "effective" project types, combined treatment effects are positive in 8 out of 10 cases for the mean project budget, are always positive for projects one standard deviation above the mean, are statistically significant in many cases, and generally have magnitudes of economic significance.[33]

Of all of the project types, mold projects appear to have had the largest effect on test scores. The average mold project ($517,156) is estimated to have improved math scores by 0.154 standard deviations and reading scores by 0.139 standard deviations. Recall that all schools that received mold remediation simultaneously received ventilation, waterproofing, and site drainage renovations, and two of the schools also received roof repairs. Given this overlap and the large effect of mold projects, one concern with the results discussed above is that mold remediation may be driving the results in ventilation, roof, waterproofing, and site drainage specifications. To investigate this possibility, columns labeled "No Mold" report results when mold projects are removed from the treatment group in each specification.[34] For ventilation projects, combined treatment effects are very similar across specifications, both in terms of magnitude and significance. For roof projects, the magnitude and significance of treatment effects is substantially reduced. And, in the absence of mold remediation, waterproofing and site drainage projects appear to have no sizable or significant effect on test scores.

Taken together, results given in Table 2 suggest that (i) projects that included

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[33] While the coefficient on $after * budget$ is generally positive and significant, the coefficient on $after$ is generally negative and occasionally significant. This would imply that very low budget projects have a *negative* effect on test scores. There are at least a couple of explanations for this. The first concerns the model specification, which imposes a linear effect of project budget on academic outcomes once expenditures are positive. However, it is possible that non-linearities exist such as an expenditure threshold that must be met before we should expect to see academic improvements. This could be because small budget projects are not likely to equally affect the entire school such that the treated group may consist largely of untreated students for whom we should not expect to see academic improvements. This could be because small budget projects are innately different in their ability to improve IAQ. For example, perhaps small budget projects reflect preventative measures while bigger budget projects reflect "clean up" efforts. In either case combining near-zero treatment effects for small budget projects with linear-in-budget treatment effects for projects above some expenditure threshold will result in a positive coefficient on $after * budget$ and a negative coefficient on $after$. In spite of this possible misspecification, the estimates should still give us a good idea of treatment effects above this threshold. A second explanation is that treatment effects are, in fact, negative for small budget projects. It seems plausible that renovations are generally disruptive. If so, it may be the case that improvements to IAQ must be sizable enough – and so must expenditures – in order to overcome the negative disruptive effect of renovations. In any case, these results rarely suggest a negative and significant effect of in-sample projects on test scores. See, for example, Figure 4.

[34] In these specifications, the treatment effect is only being identified by schools that did not have mold remediation. However, post-renovation observations for schools with mold remediation are still included in the sample to help control for grade effects, teacher effects, and so on. Removing these schools from the sample entirely does not qualitatively change the results.

mold remediation improved test scores, (ii) waterproofing, site drainage, and crawl space projects had no significant effect on test scores, and (iii) the effect of ventilation and roof projects on test scores depends on project expenditures.[35] To better illustrate the varying effects of these latter projects, Figure 4 reports combined treatment effects for ventilation and roof projects across a range of expenditures. Estimates from columns labeled "No Mold" in Table 2 are used to construct the treatment effects shown in Figure 4. In each graph, treatment effects are illustrated by a black line with 90% confidence intervals in gray. Graphs are split into four regions depending on the sign and significance of treatment effects using the following notation: (1) negative and significant; (2) negative and insignificant; (3) positive and insignificant; and (4) positive and significant. Budget distributions for projects classified as treated are overlaid to illustrate the fraction of projects falling into each of these four regions. In terms of expenditures, the upper half of ventilation projects had a positive and significant effect on at least one test score, while the lower half generally had no significant effect. However, for roof repairs, only the largest three (of 35) projects appear to significantly affect test scores. Because project budget distributions vary substantially across mold, ventilation, and roof projects, it is difficult to determine whether the estimated differences in treatment effects across these three project types is due to differences in expenditures or differences in effectiveness, but likely it is both.

Table 3 presents results from specifications that distinguish between one and two years post-renovations.[36] As discussed above, the coefficients on *2yrs_after* and *2yrs_after*budget* jointly describe the differential effect of renovations on test scores in the second year post-renovations relative to the first. If these coefficients are not statistically different from zero, the effect of renovations on test scores is essentially constant across both post-renovation years. Indeed, Table 3 suggests that this is the case. The p-values from joint significance tests of the two second-year coefficients are reported in brackets. None of the second-year coefficients are individually or jointly significant in any specification. Furthermore, the magnitudes of these coefficients relative to their first-year counterparts are quite small. Finally, the combined second-year treatment coefficients (not shown) are positive, albeit small and insignificant. One implication of these results is that the treatment effect is effectively even larger since the boost in test scores persists for multiple years.

School districts are often more interested in the percentage of students that pass

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[35] The fact that treatment effects appear to be quite different across projects types provides additional evidence that changes in air quality, rather than some other facet of renovations, is driving results. For example, there is no reason to believe that crawl space repairs and ventilation improvements would result in differing school appearance. Both involve replacing or modifying ductwork hidden behind a facade, one generally in the ceiling and the other the floor. However, given the studies discussed in Section 2, there is reason to believe that ventilation improvements might have a greater impact on IAQ. If so, then these results are consistent with the hypothesis that IAQ changes, specifically, are improving test scores.

[36] To conserve space, only one specification for Ventilation and Roof, which includes mold projects, is reported. Results are qualitative the same when mold projects are omitted.

standardized tests rather than the mean score. For this reason, Table 4 presents results from linear probability models in which the dependent variable, P_{ist}, is equal to 1 if student i passed the relevant test in school year y and is equal to 0 otherwise. Mold, ventilation, and roof projects appear to (weakly) improve math and reading scores. For mold and ventilation, projects with average expenditures significantly increase the probability of passing the reading test by 3.8% and 2.6%, respectively. However, the effect of these projects on math pass rates is both smaller and less precisely estimated. In general, larger budget mold, ventilation, and roof projects significantly improve test pass rates and the estimated effects are quite large.

5.2 Attendance

Table 5 reports estimates for school attendance when both $after$ and $after * budget$ are used to capture the effect of renovations. The dependent variable is measured as a percentage from 0 to 100 so coefficients report percentage changes in attendance. Table 5 provides very little evidence that IAQ-renovations had any effect on attendance rates. Very little is significant and the magnitudes of the estimates are also relatively small. For example, the estimated effect of the average mold remediation project on attendance is 0.068% and this is not precisely estimated. Given a typical school year length of 179 days, this corresponds to an (insignificant) increase of 0.12 days per school year. In addition to the regressions reported in Table 5, I estimate a variety of other specifications. However, I find no consistent evidence of any significant effect of renovations on school attendance.

5.3 Robustness Checks

Identification of a treatment effect requires that no omitted factors that also affect academic outcomes vary systematically with the timing of renovations. In this section, I consider two such possibilities. The first concerns school expenditures. As discussed in Section 4, no other capital projects were completed during the sample period studied here. However, annual school operating expenditures do vary from year to year. The Texas Education Agency (TEA) collects and reports various public school data including annual operating expenditures. These expenditures cover a broad range of activities, consisting of expenditures on instruction, instructional leadership, school leadership, and other campus costs which include resource centers and libraries, curriculum and instructional staff development, support services, including guidance and counseling, social work and health services, food services, cocurricular/extracurricular activities, plant maintenance and operations, security and monitoring services, and data processing services.[37] This information is available at the school level and so can be directly controlled for in the regression analysis. These results are shown in

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[37] For more information, refer to the TEA's Academic Excellence Indicator System available at http://ritter.tea.state.tx.us/perfreport/aeis.

the first three columns of Table 6 and are directly comparable to columns 1, 3, and 5 in Table 2. Coefficient point estimates as well as combined treatment effects are virtually unchanged with the inclusion of annual school operating expenditures suggesting that variations in school expenditures – either capital or operating – are not confounding identification.

Next, I consider the possibility that "better" students re-sort after renovations such that students that remain at one school have better peers post-renovations than pre-renovations, which could positively affect test scores. Because students and teachers can be paired in each school year, it is possible to construct classroom composition variables by calculating the share of specific groups of students matched to student $i's$ homeroom teacher in school year y. To control for possible peer effects, in addition to class size, the results shown in the last three columns of Table 6 also include the share of students in each of the following eleven demographic groups: female, Native American, Asian, Black, Hispanic, limited English proficiency, special education, gifted, at risk, and economically disadvantaged.[38] These results are again directly comparable to columns 1, 3, and 5 in Table 2. As with operating expenditures, the inclusion of these classroom variables has virtually no effect on estimated treatment effects.

6 Discussion & Conclusion

The completion of numerous indoor air quality-related renovation projects provided the opportunity to analyze the effect of indoor air quality on academic outcomes, a school input that has been little studied. The quasi-natural experimental design of the renovations and the availability of student-level panel data make it possible to use robust empirical methods that control for time-constant unobserved heterogeneity in order to uncover the causal effects of IAQ-renovations. I find that IAQ-renovations result in improved standardized math and reading test scores. Improvements are observed following the completion of mold remediation and ventilation improvements and, to a much lesser extent, roof repairs. No improvements are observed for waterproofing, site drainage, and crawl space projects. The average mold project (~$500,000) improved test scores by 0.14-0.15 standard deviations (sds) and the average ventilation project (~$300,000) improved test scores by 0.04-0.09 sds. Both project types significantly increased the probability of passing the reading test. Larger budget projects had even larger and more significant effects on test scores. Contrary to the effects on test scores, I do not find that school attendance rates respond in any consistent or significant way to IAQ-renovations. This suggests that improvements in indoor air quality induced by the renovation projects were not substantial enough to affect attendance rates, but were substantial enough to affect learning ability. And, because no attendance effect was observed, the entire change in test scores

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[38] "Caucasian" is the omitted ethnicity category.

is attributable to improved school “quality” rather than increased school “quantity”.

Determining whether or not improvements to indoor air quality led to improvements in test scores was the primary goal of this paper. A secondary question is whether or not this is a cost-effective method. For a basic comparison, I provide a quick, back of the envelope cost-benefit analysis of class size reductions and IAQ-renovations. In a well-designed study, Rivkin, Hanushek and Kain (2005) find that class size reductions of 10 to 13 students lead to an approximate 0.10 standard deviation improvement in standardized math and reading test scores. In a study of California’s class size reduction reform, Reichardt (2000) estimates the cost of reducing class sizes from 24 to 15 students to be approximately $1,305 per student. Combining these studies suggests a per student cost of more than $1,305 to achieve a 0.10 standard deviation improvement in test scores via class size reductions. Since the bulk of the expense is teacher salaries, this cost would largely be incurred on an annual basis in order to maintain the improvement in test scores. Given the average elementary school size of 535 students – and a tight distribution about the mean – in the present study, my results suggest that an outlay of approximately $970 per student on mold remediation leads to a 0.14-0.15 standard deviation improvement in test scores. And, unlike class size reductions, these costs would *not* be incurred on an annual basis since it appears that the benefits from renovations last more than one year. While these calculations are rough and certainly have wide confidence intervals, they provide support that IAQ-renovations may be a cost-effective way to improve student test scores.

It is important to remember that the ability of renovations to improve test scores relies on indoor air quality being suboptimal in the first place. Comparison of pre-renovation indoor CO_2 levels, a proxy for ventilation rates, in the school district studied here with other school districts in the U.S. and elsewhere, reveals that the schools analyzed in this study are not unusual. Many of the schools in this and other studies have indoor CO_2 levels above the ASHRAE recommended maximum, which suggests that poor ventilation is a common problem and that the improvements in test scores found here as a result of ventilation improvements may be replicated elsewhere.

The results discussed in this paper were derived from one set of data so the implications should be weighed accordingly. However, the predicted academic benefits of improved indoor air quality are quite large, especially given the associated costs, which strongly suggests that more opportunities to soundly test this relationship be identified. Furthermore, not only can cleaner indoor air improve academic performance, but student health may also improve if changes in air quality are large enough and original levels of air quality are poor enough. Given the long-term consequences of both childhood health and human capital accumulation, these are important relationships to better understand.

References

Bako-Biro, Zsolt, Derek Clements-Croome, Neena Kochhar, Hazim Awbi, and M. Williams. 2012. “Ventilation Rates in Schools and Pupils’ Performance.” *Building and Environment*, 48(1): pp. 215–223.

Bishop, John. 1991. “Achievement, Test Scores, and Relative Wages.” In *Workers and Their Wages.* , ed. Marvin Kosters, 146–186. Washington, DC:The AEI Press.

Cellini, Stephanie Riegg, Fernando Ferreira, and Jesse Rothstein. 2010. “The Value of School Facility Investments: Evidence from a Dynamic Regression Discontinuity Design.” *The Quarterly Journal of Economics*, 125(1): pp. 215–261.

Chay, Kenneth Y., and Michael Greenstone. 2003. “The Impact of Air Pollution on Infant Mortality: Evidence from Geographic Variation in Pollution Shocks Induced by a Recession.” *The Quarterly Journal of Economics*, 118(3): pp. 1121–1167.

Currie, Janet, and Matthew Neidell. 2005. “Air Pollution and Infant Health: What Can We Learn from California’s Recent Experience?” *The Quarterly Journal of Economics*, 120(3): pp. 1003–1030.

Currie, Janet, Eric A. Hanushek, E. Megan Kahn, Matthew Neidell, and Steven G. Rivkin. 2009. “Does Pollution Increase School Absences?” *The Review of Economics and Statistics*, 91(4): pp. 682–694.

Daisey, Joan, William Angell, and Michael Apte. 2003. “Indoor Air Quality, Ventilation and Health Symptoms in Schools: An Analysis of Existing Information.” *Indoor Air*, 13(1): pp. 53–64.

Duflo, Esther, Michael Greenstone, and Rema Hanna. 2008. “Indoor Air Pollution, Health and Economic Well-being.” *Working Paper, Massachusetts Institute of Technology*, pp. 1–22.

Grogger, Jeff, and Eric Eide. 1995. “Changes in College Skills and the Rise in the College Wage Premium.” *The Journal of Human Resources*, 30(2): pp. 280–310.

Hanushek, Eric A. 2003. “The Failure of Input-Based Schooling Policies.” *The Economic Journal*, 113(485): pp. F64–F98.

Hanushek, Eric A., and Dennis D. Kimko. 2000. “Schooling, Labor-Force Quality, and the Growth of Nations.” *The American Economic Review*, 90(5): pp. 1184–1208.

Haverinen-Shaughnessy, Ulla, Demetrios Moschandreas, and Richard Shaughnessy. 2011. “Association Between Substandard Classroom Ventilation Rates and Students’ Academic Achievement.” *Indoor Air*, 21(2): pp. 121–131.

Jones, John T., and Ron W. Zimmer. 2001. "Examining the Impact of Capital on Academic Achievement." *Economics of Education Review*, 20(6): pp. 577–588.

Lavy, Victor, Avraham Ebenstein, and Sefi Roth. 2012. "The Impact of Air Pollution on Cognitive Performance and Human Capital Formation." *Working Paper, University of Warwick*, pp. 1–38.

Mendell, Mark, and Garvin Heath. 2005. "Do Indoor Pollutants and Thermal Conditions in Schools Influence Student Performance? A Critical Review of the Literature." *Indoor Air*, 15(1): pp. 27–52.

Neal, Derek A., and William R. Johnson. 1996. "The Role of Premarket Factors in Black-White Wage Differences." *Journal of Political Economy*, 104(5): pp. 869–895.

Neidell, Matthew. 2004. "Air Pollution, Health, and Socio-economic Status: The Effect of Outdoor Air Quality on Childhood Asthma." *Journal of Health Economics*, 23(6): pp. 1209–1236.

O'Neill, June. 1990. "The Role of Human Capital in Earnings Differences Between Black and White Men." *The Journal of Economic Perspectives*, 4(4): pp. 25–45.

Pierce, Brooks, and Finis Welch. 1996. "Changes in the Structure of Wages." In *Improving Americas Schools: The Role of Incentives.* , ed. Eric Hanushek and Dale Jorgenson, 53–73. Washington, DC:National Academy Press.

Reichardt, Robert. 2000. "The Cost of Class Size Reduction: Advice for Policymakers." PhD diss. RAND Graduate School.

Rivkin, Steven G., Eric A. Hanushek, and John F. Kain. 2005. "Teachers, Schools, and Academic Achievement." *Econometrica*, 73(2): pp. 417–458.

Sanders, Mark. 2008. "Assessment of Indoor Air Quality in Texas Elementary Schools." PhD diss. The University of Texas at Austin.

Sanders, Nicholas. 2012. "What Doesn't Kill You Makes You Weaker: Prenatal Pollution Exposure and Educational Outcomes." *Journal of Human Resources*, 47(3): pp. 826–850.

Satish, Usha, Mark Mendell, Krishnamurthy Shekhar, Toshifumi Hotchi, Douglas Sullivan, Siegfried Streufert, and William Fisk. 2012. "Is CO_2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO_2 Concentrations on Human Decision-Making Performance." *Environmental Health Perspectives*, 120(12): pp. 1671–1677.

Smedje, Greta, and Dan Norback. 2000. "New Ventilation Systems at Select Schools in Sweden - Effects on Asthma and Exposure." *Archives of Environmental Health*, 55(1): pp. 18–25.

Wargocki, Pawel, and David Wyon. 2007*a*. "The Effects of Air Supply Rate and Supply Air Filter Condition in Classrooms on the Performance of Schoolwork by Children." *HVAC&R Research*, 13(2): pp. 165–191.

Wargocki, Pawel, and David Wyon. 2007*b*. "The Effects of Moderately Raised Classroom Temperatures and Classroom Ventilation Rate on the Performance of Schoolwork by Children." *HVAC&R Research*, 13(2): pp. 193–220.

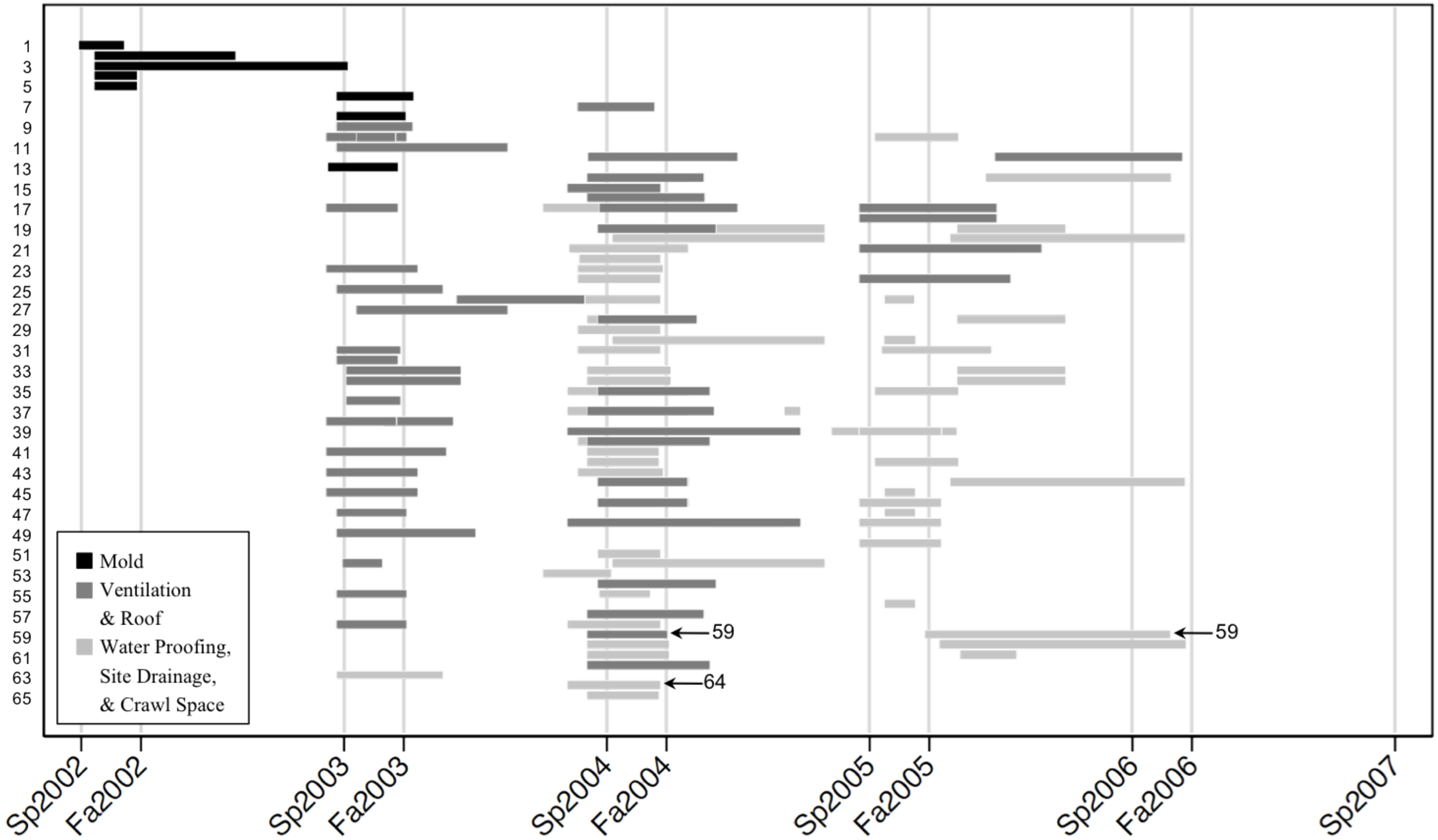

Figure 1: Timeline of Renovation Projects

Notes: The x-axis captures time, where "Fa" denotes the beginning of the fall semester and "Sp" the end of the spring semester so that the narrow columns correspond to summer vacations. The y-axis identifies each of the 65 schools that received renovations between 2002 and 2007. Schools are sorted by total renovation expenditures so that School 1 received the most funding and School 65 the least. Shaded horizontal bars indicate the timing and duration of renovations. All renovation projects are first mapped in light gray. Renovations including ventilation improvements and/or roof repairs, but not mold remediation, are mapped on top in medium gray. Finally, renovations including mold remediation are mapped on top of this in black.

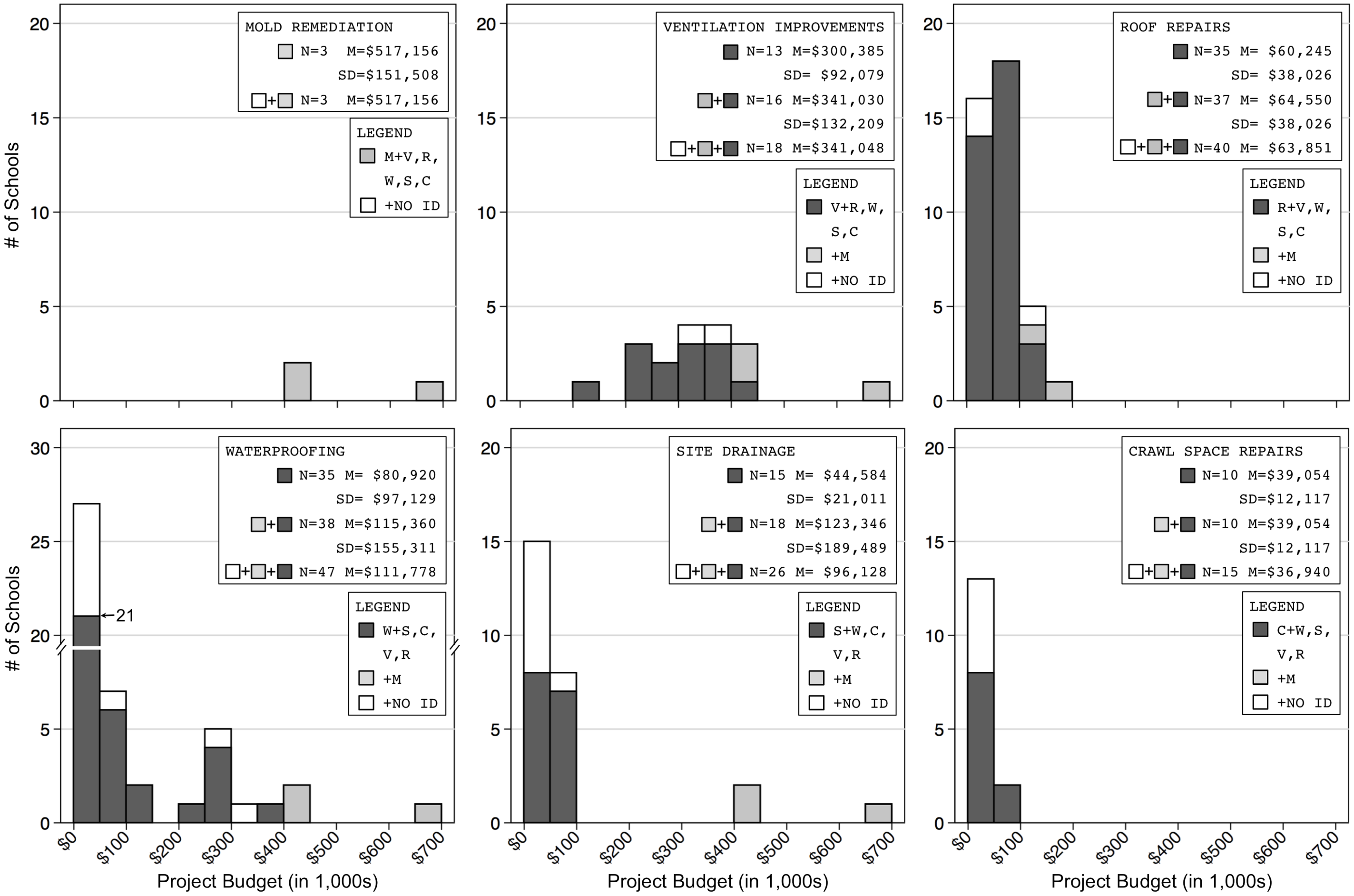

Figure 2: Distributions of Renovation Expenditures by Protect Type

Notes: The number of schools with projects in each budget category is captured by the y-axis and the level of expenditures by the x-axis. Projects are color coded according to the variety of other project types being completed simultaneously. Legends use the following shorthand to identify projects: "M"-mold, "V"-ventilation, "R"-roof, "W"-waterproofing, "S"-site drainage, "C"-crawl space, and "NO ID"-not identified. Summary statistics are given for several samples where "N" denotes the number of schools in the sample, "M" the mean budget, and "SD" the standard deviation. The histogram for ventilation, for example, shows that thirteen schools received ventilation improvements that *may* have been accompanied by roof repairs, waterproofing, site drainage, or crawl space renovations $(+R, W, S, C)$. An additional three schools also received mold remediation $(+M)$ and another two are not identified (+*NO ID*).

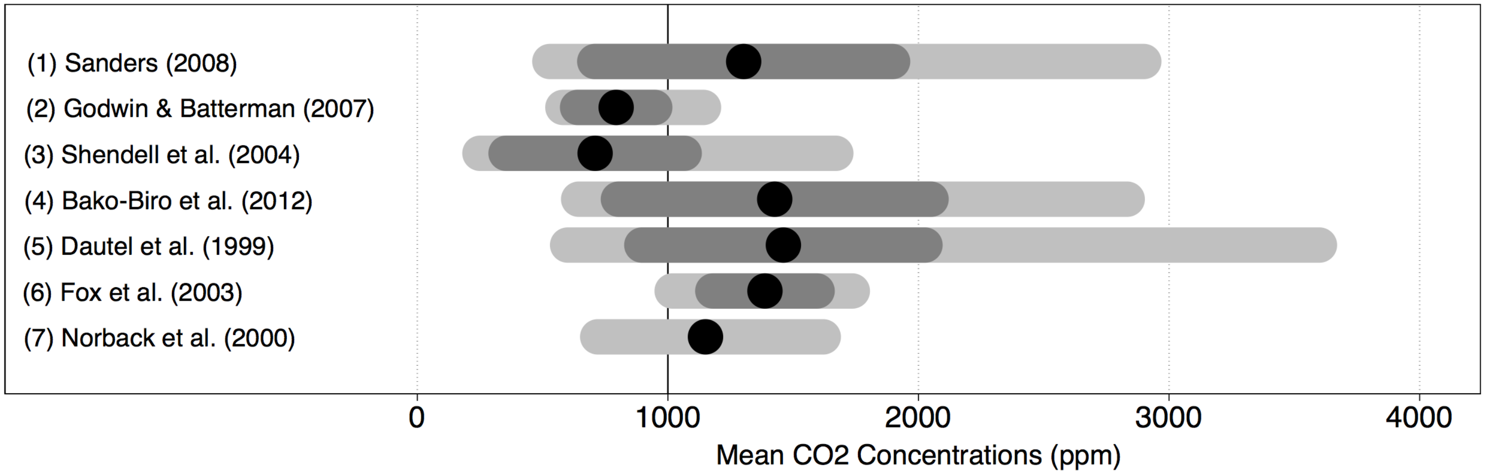

Figure 3: Distributions of Mean Classroom CO_2 Concentrations Across Seven Studies

Notes: These studies examine elementary school classrooms in (1) Texas (2) Michigan, (3) Washington and Idaho, (4) Reading, England, (5) Texas, (6) South Carolina, and (7) Uppsala, Sweden, respectively. CO_2 is measured in parts per million (ppm). For each study, and when available, the mean of all measured classrooms is depicted by a black dot, one standard deviation above and below the mean by the medium gray region, and the minimum and maximum by the extremes of the light gray region. The vertical line at 1,000ppm corresponds to the maximum indoor CO_2 concentration recommended by ASHRAE.

Table 1: *Estimates of the Impact of IAQ Renovations on TAKS Scores in Math and Reading*

Variables	All	Mold	Ventilation	Roof	Water	Site	Crawl
			Panel A: Math Scores				
after	0.021	0.165 **	0.059	0.027	0.000	0.034	-0.118
	(0.036)	(0.065)	(0.061)	(0.040)	(0.045)	(0.064)	(0.084)
Observations	37,286	19,238	21,018	23,387	23,692	21,094	19,886
Students	16,318	9,083	9,762	10,755	10,777	9,878	9,395
			Panel B: Reading Scores				
after	0.002	0.147 **	0.098 **	0.041	0.034	-0.003	-0.064
	(0.032)	(0.068)	(0.043)	(0.040)	(0.037)	(0.040)	(0.045)
Observations	36,982	19,023	20,820	23,176	23,471	20,906	19,686
Students	16,171	8,978	9,668	10,646	10,671	9,782	9,298

Notes: Columns report regression results for different treatment classifications. For example, "Mold" classify only projects that include mold remediation as treatment. In addition to $after$, all regressions include $classsize$, $distexp$, $salary$, year indicators, grade indicators, and student-school fixed effects. Robust standard errors, clustered by school, are shown in parentheses below point estimates. Significance is denoted as follows: *** p<0.01, ** p<0.05, * p<0.1.

Table 2: *Estimates of the Impact of IAQ Renovations on TAKS Scores Incorporating Project Expenditures*

	Mold	Ventilation		Roof		Water		Site		Crawl
Variables	All	All	No Mold	All	No Mold	All	No Mold	All	No Mold	All
					Panel A: Math Scores					
after	-0.260**	-0.271**	-0.439**	-0.097	-0.076	-0.040	-0.012	-0.038	-0.039	-0.102
	(0.108)	(0.109)	(0.182)	(0.074)	(0.078)	(0.057)	(0.056)	(0.087)	(0.181)	(0.285)
*after*budget*	0.080***	0.094***	0.158***	0.175***	0.140*	0.032**	-0.030	0.043**	0.062	-0.037
	(0.016)	(0.024)	(0.057)	(0.066)	(0.082)	(0.016)	(0.036)	(0.018)	(0.295)	(0.793)
TE/Mean Budget†	0.154***	0.049	0.035	0.016	0.009	-0.003	-0.037	0.015	-0.011	-0.116
	(0.041)	(0.056)	(0.061)	(0.041)	(0.043)	(0.045)	(0.052)	(0.068)	(0.076)	(0.081)
TE/Mean + 1 sd†	0.276***	0.174***	0.180**	0.082**	0.055	0.047	-0.066	0.097**	0.002	-0.121
	(0.036)	(0.056)	(0.080)	(0.033)	(0.038)	(0.039)	(0.066)	(0.044)	(0.071)	(0.149)
Observations	19,238	21,018	20,395	23,387	23,076	23,692	23,069	21,094	20,471	19,886
Students	9,083	9,762	9,507	10,755	10,656	10,777	10,522	9,878	9,623	9,395
					Panel B: Reading Scores					
after	-0.223	-0.101	-0.201*	-0.065	-0.046	0.003	0.016	-0.073	0.001	-0.028
	(0.134)	(0.067)	(0.120)	(0.057)	(0.053)	(0.045)	(0.045)	(0.049)	(0.084)	(0.118)
*after*budget*	0.070***	0.057***	0.097***	0.146***	0.109**	0.025**	0.002	0.042***	-0.128	-0.088
	(0.020)	(0.014)	(0.035)	(0.040)	(0.041)	(0.012)	(0.032)	(0.010)	(0.196)	(0.233)
TE/Mean Budget†	0.139***	0.092**	0.090*	0.030	0.019	0.031	0.018	-0.022	-0.056	-0.062
	(0.042)	(0.043)	(0.046)	(0.043)	(0.044)	(0.038)	(0.043)	(0.041)	(0.047)	(0.045)
TE/Mean + 1 sd†	0.245***	0.168***	0.179***	0.085**	0.056	0.070*	0.019	0.058	-0.082	-0.073*
	(0.031)	(0.044)	(0.052)	(0.041)	(0.044)	(0.036)	(0.058)	(0.036)	(0.072)	(0.041)
Observations	19,023	20,820	20,213	23,176	22,875	23,471	22,864	20,906	20,299	19,686
Students	8,978	9,668	9,420	10,646	10,551	10,671	10,423	9,782	9,534	9,298

Notes: Columns report regression results for different treatment classifications. For example, "Mold" classify only projects that include mold remediation as treatment. Specifications labeled "No Mold" remove mold projects from the treatment group. In addition to $after$ and $after * budget$, all regressions include *classsize*, *distexp*, *salary*, year indicators, grade indicators, and student-school fixed effects. Robust standard errors, clustered by school, are shown in parentheses below point estimates. †Combined treatment effects ("TE"), with standard errors below, are reported for (i) the mean budget of all projects classified as "treated" in that specification and (ii) the mean budget plus one standard deviation. Corresponding budget statistics can be found in Figure 2. Significance is denoted as follows: *** p<0.01, ** p<0.05, * p<0.1.

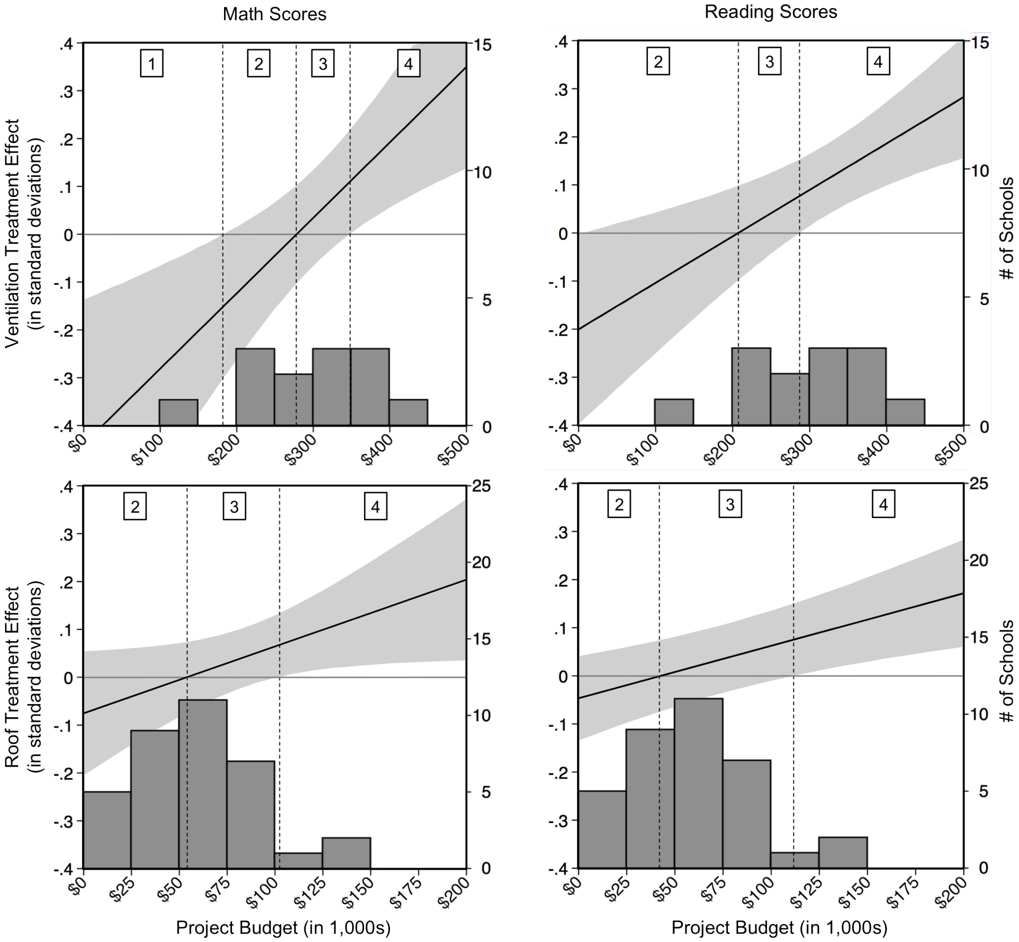

Figure 4: Treatment Effects for Ventilation and Roof Projects

Notes: Math and reading treatment effects for ventilation and roof projects are constructed using estimates from columns labeled "No Mold" in Table 2. Treatment effects, measured in standard deviations, are illustrated by a black line, with 90% confidence interval in gray. Graphs are split into four regions depending on the sign and significance of treatment effects using the following notation: (1) negative and significant; (2) negative and insignificant; (3) positive and insignificant; and (4) positive and significant. Budget distributions for projects classified as treated are overlaid. The number of schools falling into each budget category is given by the right hand side y-axis.

Table 3: *Estimates of the Impact of IAQ Renovations on TAKS Scores One and Two Years Post-Renovations*

	Panel A: Math Scores			Panel B: Reading Scores		
Variables	Mold	Ventilation	Roof	Mold	Ventilation	Roof
after	-0.247 *	-0.244 **	-0.087	-0.188	-0.045	-0.050
	(0.129)	(0.122)	(0.077)	(0.114)	(0.059)	(0.056)
*after*budget*	0.075 ***	0.089 ***	0.156 **	0.062 ***	0.048 ***	0.137 ***
	(0.021)	(0.026)	(0.070)	(0.017)	(0.012)	(0.042)
2yrs_after	0.086	0.073	0.037	0.127	0.004	-0.015
	(0.128)	(0.060)	(0.062)	(0.084)	(0.035)	(0.041)
*2yrs_after*budget*	-0.004	-0.003	-0.009	-0.003	0.002	0.004
	(0.006)	(0.004)	(0.009)	(0.004)	(0.003)	(0.008)
p-value	[0.784]	[0.481]	[0.570]	[0.250]	[0.689]	[0.903]
Observations	19,238	20,725	22,622	19,023	20,529	22,409
Students	9083	9616	10357	8978	9523	10248

Notes: See Table 2. Two additional variables are added to Equation (1) to capture any differential effect of renovations across time post-renovations: (i) *2yrs_after* and (ii) *2yrs_after*budget*. Now, the coefficients on *after* and *after*budget* capture the effect of renovations in the first year post-renovations and the combination of all four treatment coefficients capture the effect of renovations in the second year post-renovations. P-values from joint significance tests of the two second year treatment variables are shown in brackets below estimates.

Table 4: *Linear Probability Estimates of the Impact of IAQ Renovations on the Probability of Passing the TAKS*

	Mold	Ventilation		Roof	
Variables	All	All	No Mold	All	No Mold
			Panel A: Math Scores		
after	0.045	-0.067	-0.154 **	-0.012	-0.017
	(0.085)	(0.044)	(0.068)	(0.023)	(0.026)
*after*budget*	-0.002	0.023 **	0.054 ***	0.039 *	0.051 *
	(0.012)	(0.011)	(0.019)	(0.021)	(0.026)
TE/Mean Budget†	0.035	0.011	0.009	0.013	0.014
	(0.026)	(0.021)	(0.019)	(0.015)	(0.015)
TE/Mean + 1 sd†	0.032 *	0.042	0.058 ***	0.028 *	0.032 **
	(0.017)	(0.025)	(0.020)	(0.015)	(0.015)
Observations	19,238	21,018	20,395	23,387	23,076
Students	9,083	9,762	9,507	10,755	10,656
			Panel B: Reading Scores		
after	0.007	-0.063	-0.172 ***	-0.021	-0.026
	(0.014)	(0.040)	(0.039)	(0.019)	(0.020)
*after*budget*	0.006 ***	0.025 **	0.066 ***	0.054 ***	0.064 ***
	(0.002)	(0.012)	(0.010)	(0.017)	(0.023)
TE/Mean Budget†	0.038 ***	0.024	0.026 *	0.013	0.013
	(0.011)	(0.017)	(0.015)	(0.015)	(0.015)
TE/Mean + 1 sd†	0.048 ***	0.057 **	0.087 ***	0.034 **	0.034 *
	(0.012)	(0.025)	(0.014)	(0.016)	(0.017)
Observations	19,023	20,820	20,213	23,176	22,875
Students	8,978	9,668	9,420	10,646	10,551

Notes: See Table 2. Here, the dependent variable takes the value of 1 if student i passed the specified test in year y and takes the value of 0 otherwise. Explanatory variables are the same as those given in Equation (1).

Table 5: *Estimates of the Impact of IAQ Renovations on School Attendance*

Variables	Mold	Ventilation	Roof	Water	Site	Crawl
after	-0.110	-0.016	-0.137	-0.083	0.028	-0.248
	(0.093)	(0.290)	(0.112)	(0.073)	(0.075)	(0.200)
*after*budget*	0.035 ***	-0.019	0.097	0.019	0.012	0.795
	(0.008)	(0.073)	(0.112)	(0.018)	(0.018)	(0.481)
TE/Mean Budget†	0.068	-0.081	-0.074	-0.061	0.043	0.062
	(0.076)	(0.098)	(0.070)	(0.066)	(0.062)	(0.074)
TE/Mean + 1 sd†	0.121	-0.106	-0.037	-0.031	0.066	0.159 *
	(0.075)	(0.119)	(0.072)	(0.067)	(0.056)	(0.095)
Observations	39,976	43,356	48,630	48,989	44,090	41,810
Students	18,981	19,952	21,782	21,639	20,434	19,848

Notes: See Table 2. Results shown above are from versions of Equation (1) in which the dependent variable is school attendance rates, measured as a percentage from 0 to 100.

Table 6: *Robustness Checks*

	Controlling for School Finances			Controlling for Classroom Demographics		
Variables	Mold	Ventilation (No Mold)	Roof (No Mold)	Mold	Ventilation (No Mold)	Roof (No Mold)
			Panel A: Math Scores			
after	-0.284***	-0.426**	-0.080	-0.248**	-0.427**	-0.069
	(0.096)	(0.185)	(0.077)	(0.096)	(0.183)	(0.077)
*after*budget*	0.085***	0.153**	0.147*	0.077***	0.153***	0.127
	(0.015)	(0.058)	(0.081)	(0.014)	(0.057)	(0.080)
TE/Mean Budget†	0.154***	0.034	0.008	0.151***	0.031	0.008
	(0.038)	(0.062)	(0.043)	(0.039)	(0.062)	(0.042)
TE/Mean + 1 sd†	0.282***	0.175**	0.057	0.268***	0.172**	0.050
	(0.036)	(0.082)	(0.040)	(0.036)	(0.080)	(0.038)
Observations	19,238	20,395	23,076	19,238	20,395	23,076
Students	9,083	9,507	10,656	9,083	9,507	10,656
			Panel B: Reading Scores			
after	-0.220	-0.202	-0.045	-0.244	-0.226*	-0.041
	(0.135)	(0.124)	(0.052)	(0.154)	(0.126)	(0.052)
*after*budget*	0.069***	0.097***	0.106**	0.073***	0.104***	0.100**
	(0.020)	(0.036)	(0.041)	(0.023)	(0.037)	(0.042)
TE/Mean Budget†	0.139***	0.090*	0.019	0.135***	0.085*	0.019
	(0.041)	(0.046)	(0.044)	(0.048)	(0.045)	(0.042)
TE/Mean + 1 sd†	0.244***	0.179***	0.055	0.246***	0.180***	0.053
	(0.032)	(0.051)	(0.044)	(0.035)	(0.052)	(0.042)
Observations	19,023	20,213	22,875	19,023	20,213	22,875
Students	8,978	9,420	10,551	8,978	9,420	10,551

Notes: See Table 2. Specifications shown in Columns 1 - 3 include annual school operating expenditures. Specifications shown in Columns 4 - 6 include classroom composition variables, which are described in Section 5.3. Results are directly comparable to Columns 1, 3, and 5 in Table 2.