The Effects of School Building HVAC System Conditions on Student Academic and Behavioral Outcomes

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Abstract. There is growing awareness of the importance of school building environments for student health, well-being, and even educational outcomes. We ask in this study what role school building heating, ventilation, and air conditioning (HVAC) systems play in shaping student attendance, behavior, and learning. In particular, we extract information from school building inspection reports and link them to education records for public K-12 schools in New York State, excluding New York City schools, between the 2005-06 and 2018-19 academic years. Using a difference-in-differences approach, we find that improvements in school HVAC system conditions over time reduce student absences and suspensions and modestly increase student math and reading scores, with achievement effects particularly pronounced in schools serving high proportions of low-income students and students of color and in areas with higher air pollution. Heating and cooling system reconstructions and replacements increase student math achievement but have no effect on other outcomes, a pattern consistent with the fact that most replacements involve already-functioning systems rather than remediating unsatisfactory conditions. We conclude that targeting HVAC investments toward the schools with the greatest need has the potential to benefit not only student comfort and health, but also reduce educational inequality.

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1. Introduction

An emerging body of research shows that physical school facilities and environmental conditions can meaningfully shape student outcomes beyond the effects of classroom instruction alone. Although earlier work expressed skepticism that investments in school facilities would yield academic benefits (e.g., Hanushek, 1997), a growing number of recent causal studies find that increased capital expenditures—often used for school renovation or construction—can improve student outcomes (Biasi et al., 2025; Lafortune & Schönholzer, 2022; O'Hagan, 2025). These findings are not universal, however, and some studies find more limited or null effects (Baron, 2022; Martorell et al., 2016). This mixed evidence points to the importance of identifying which specific features of school buildings are most consequential for students.

This study focuses on one especially policy-relevant feature: heating, ventilation, and air conditioning (HVAC) systems. HVAC systems shape the air quality, ventilation, and thermal conditions students experience each day, yet inadequacies are widespread and unequally distributed. The U.S. Government Accountability Office estimated that 36,000 school buildings nationwide had inadequate HVAC systems (Nowicki, 2020), and districts serving larger shares of low-income students are more likely to report HVAC problems and other facility deficiencies (Alexander & Lewis, 2014). Despite the prevalence of these problems, evidence remains limited on whether HVAC system conditions, repairs, and replacements affect student attendance, discipline, and academic achievement.

We address this question using 14 years of school building inspection data from New York State, excluding New York City schools. We link information from public inspection reports to school-level educational outcomes from the New York State Education Department. These data allow us to conduct two complementary analyses of HVAC systems and student outcomes. First, repeated inspection ratings allow us to estimate the effects of within-school improvements or deterioration in cooling, heating, and ventilation system conditions. Second, retrospective survey questions identify the timing of major reconstructions or replacements, allowing us to estimate the effects of those specific capital projects. We also assess whether these effects differ across schools serving different student populations and across areas with varying temperature and pollution conditions.

This evidence is especially relevant given recent federal investments in school facility improvements, including HVAC repairs and upgrades (Silberstein & Roza, 2023). Some observers have questioned whether such spending is the best use of limited education dollars, arguing that schools should instead prioritize instructional time and direct academic supports (Brooks & Springer, 2024), particularly amid persistent concerns about learning loss (Lewis & Kuhfeld, 2023). But this critique rests partly on the assumption that facility investments are peripheral to academic improvement. If HVAC systems affect student health, attendance, and classroom learning conditions, these investments may be more directly connected to educational outcomes than conventional distinctions between “instructional” and “non-instructional” spending imply.

HVAC improvements could affect students through several mechanisms. Better ventilation and air filtration may improve indoor air quality, and school-based studies have linked such improvements to gains in attendance and achievement (Gilraine, 2025; Persico & Fuller, 2025; Stafford, 2015). Cleaner air may reduce exposure to pollutants, allergens, mold, and infectious particles, thereby limiting illness and improving students’ ability to concentrate. Well-functioning heating and cooling systems may also improve thermal comfort during periods of extreme heat or cold (Carlson & Shepardson, 2024; Park et al., 2020). Because outdoor pollution exposure has also been linked to worse attendance and achievement (Chung et al., 2025; Duque & Gilraine, 2022; Heissel et al., 2022; Marcotte, 2017; Persico & Venator, 2021), HVAC systems may be especially consequential in higher-pollution areas. These mechanisms suggest that HVAC conditions may influence achievement both indirectly, through improved health and attendance, and directly, through better classroom learning conditions.

Our descriptive analyses reveal substantial inequalities in exposure to poor school environments. Economically disadvantaged, Black, and Hispanic students are more likely to attend schools with unsatisfactory building conditions, air quality, heating systems, and ventilation systems. We also find that many schools with nonfunctional heating systems are located in areas that regularly experience below-freezing temperatures, many with nonfunctional cooling systems are located in areas that experience extreme heat, and many with nonfunctional ventilation systems are located in areas with high particulate pollution. To the extent that these systems affect student health or learning, inadequate HVAC conditions could exacerbate existing health and educational inequalities.

Using panel fixed-effects models and difference-in-differences estimators (Callaway & Sant'Anna, 2021), we separately estimate the effects of changes in inspectors' system condition ratings and the effects of reported major reconstructions or replacements. We find that satisfactory cooling system conditions are associated with 2% reductions in student absence and suspension rates and a 0.03-standard-deviation increase in reading scores, relative to unsatisfactory or nonfunctional systems. Satisfactory heating conditions reduce absences by 3% and suspensions by 4% and increase math scores by 0.05 standard deviations. Satisfactory ventilation conditions reduce absences by 2% and suspensions by 6% and increase math scores by 0.03 standard deviations. Test score gains are concentrated in schools located in higher-pollution areas and are largest in schools serving greater shares of students of color and low-income students. These patterns suggest that targeting investments toward the lowest-quality systems could help narrow persistent opportunity gaps.

For HVAC system reconstructions and replacements, we find no detectable effects on absences, suspensions, or reading achievement, but significant math gains of approximately 0.03 standard deviations for cooling systems and 0.04 standard deviations for heating systems. These more limited effects may reflect that most reconstructed or replaced systems were already rated satisfactory before the project, suggesting that many replacements represent routine maintenance rather than remediation of poor conditions and therefore produce smaller environmental improvements than transitions from unsatisfactory to satisfactory condition. Overall, the findings underscore the value of maintaining high-quality school HVAC systems and indicate that investments targeted toward schools with the greatest facility needs are likely to yield the largest returns for student well-being and educational opportunity.

This study contributes to a growing causal literature on the educational effects of school-based investments and interventions designed to improve environmental conditions. The closest prior studies examine capital spending directed toward HVAC systems (Biasi et al., 2025), school HVAC and air-filtration upgrades (Persico & Fuller, 2025), ventilation and mold remediation projects (Stafford, 2015), air filters and portable air purifiers (Bonan et al., 2025; Gilraine, 2025), and the role of school air conditioning in mitigating the effects of heat on learning (Park et al., 2020). Unlike the broader literature on pollution exposure and achievement (see Nguyen, 2026), these studies evaluate changes that schools or districts can undertake directly and measure their effects on achievement, attendance, and other educational outcomes.

Collectively, they suggest that investments in school environmental quality can improve student outcomes, although estimated effects vary across interventions and settings.

Our study extends this research in several ways. First, rather than identifying HVAC investments through expenditures or bond authorizations (Biasi et al., 2025) or participation in a particular upgrade program (Persico & Fuller, 2025), we use repeated building inspections to observe the physical and functional condition of HVAC systems directly and estimate the effects of within-school changes over 14 years. Second, by separately examining system condition and major reconstructions or replacements, we distinguish improvements in system functionality from projects that may involve routine replacement of already functional systems—an important consideration for interpreting and targeting facility investments (Bonan et al., 2025; Gilraine, 2025; Persico & Fuller, 2025; Stafford, 2015). Finally, we distinguish among heating, cooling, and ventilation systems; estimate effects on attendance, suspensions, reading, and math; and examine whether those effects vary with local temperature and pollution. The study therefore provides evidence on which HVAC deficiencies appear most consequential, under what environmental conditions, and where investments may generate the greatest educational and equity benefits.

1.1. School Environmental Conditions, HVAC Investments, and Student Outcomes

A longstanding public health literature documents the importance of building conditions and ventilation for human health, comfort, and productivity. Within schools, studies consistently show that higher ventilation rates and better indoor air quality are associated with reduced illness-related absences, improved student respiratory health, and stronger academic performance (Shendell et al., 2004; Wargocki, 2008; Simons et al., 2010; Mendell et al., 2013). These connections between ventilation, health, attendance, and learning underscore why the study of HVAC systems in schools warrants particular attention.

Evidence directly linking air pollution to student outcomes has grown in recent years. Short-run increases in pollution reduce test performance (Ebenstein et al., 2016; Marcotte, 2017), while longer-term exposure near schools or residences similarly leads to lower achievement and other adverse educational outcomes (Rau et al., 2015; Persico & Venator, 2021). To address the nonrandom location and timing of pollution exposure, studies use a range of creative research designs, including thermal inversions that trap pollutants near the ground (Balakrishnan & Tsaneva, 2021), changes in wind direction that shift daily pollution exposure (Chung et al., 2025), and variation in the timing and location of school-bus retrofits (Austin, 2019). Synthesizing 28 causal studies, Nguyen (2026) estimates that pollution exposure reduces student achievement by an average of approximately 0.02 standard deviations. Although this literature does not generally evaluate changes that schools can undertake directly, it provides strong causal evidence that air quality can shape student learning and school participation.

A parallel line of work documents the academic consequences of extreme temperatures. Hot days substantially reduce learning, with especially large effects for historically marginalized student groups (Park et al., 2020). Using repeated PSAT scores for approximately 10 million students, Park et al. find that a 1°F hotter school year reduces achievement by approximately 0.002 standard deviations and that air conditioning substantially offsets these effects. Temperature exposure over the school year, rather than test-day conditions alone, also appears consequential for academic achievement, and studies across multiple climates find that both heat and cold can depress test performance (Johnston et al., 2021; Carlson & Shepardson, 2024). Collectively, this research suggests that thermal conditions—like air quality—are important drivers of learning environments and motivates our examination of whether HVAC conditions matter differently across local temperature and pollution contexts.

The studies most closely related to ours evaluate school-based investments or interventions designed to improve environmental conditions and measure their effects on educational outcomes. Stafford (2015) uses the staggered timing of indoor-air-quality renovations across nearly all elementary schools in a single Texas district over five years. She finds that mold remediation improved math and reading scores by approximately 0.15 and 0.14 standard deviations, respectively, while ventilation improvements raised scores by 0.07 to 0.11 standard deviations; attendance rates were unresponsive. Gilraine (2025) examines the installation of air filters in Los Angeles schools following the Aliso Canyon gas leak. Using a spatial regression discontinuity design comparing schools just inside and outside the five-mile intervention boundary, he finds that air filters increased math scores by approximately 0.20 standard deviations and produced a similarly sized, though less precisely estimated, increase in English scores.

More recent studies examine air-quality interventions using statewide administrative data or experimental designs. Persico and Fuller (2025) link population-level student data from North Carolina from 2020 through 2023 to the timing of school HVAC and air-filtration upgrades funded through state capital programs and federal pandemic relief. Using student and school fixed effects, they find that air-purification upgrades improved test scores by 0.033 standard deviations and grades by 10 percent of a letter grade, while reducing absence rates by 0.2 percentage points and chronic absenteeism by 0.8 percentage points. Bonan et al. (2025) randomly installed portable air purifiers across 95 classrooms and approximately 2,050 students in five Italian schools. The intervention reduced classroom particulate matter by 32 percent and resulted in an estimated 1.34 fewer missed days per student annually, although effects varied across the school year. These studies suggest that relatively targeted improvements in filtration and indoor air quality can positively affect student outcomes.

Biasi et al. (2025) provide the most comprehensive causal evidence on school capital investment. They construct a national panel of school bond elections, classify the investments described in each proposal, and use a dynamic regression discontinuity design around close votes to estimate the effects of different types of capital spending. They find that investments in building renovation and environmental quality—including HVAC systems, roofing, and toxic-material remediation—produce especially large achievement gains, with the highest returns in socioeconomically disadvantaged districts. HVAC-related bond authorizations increase test scores by more than 0.20 standard deviations over three to six years. In a related New York City study, O'Hagan (2025) uses a difference-in-differences design to examine new or substantially renovated school buildings, finding a small increase in attendance after several years but small and imprecisely estimated effects on math and ELA scores. These studies demonstrate that the effects of school capital investments vary by their type and context. Unlike our data, however, neither observes the physical and functional condition of individual HVAC systems.

Prior studies establish that cleaner air, more moderate temperatures, and school facility investments can improve student outcomes. Less is known, however, about how the condition of specific HVAC systems shapes attendance, behavior, and learning across schools facing different environmental risks. By linking repeated inspections to student outcomes, our study brings these strands of research together. It provides a more direct view of how heating, cooling, and ventilation systems matter in practice, while also distinguishing changes in observed system condition from major reconstruction or replacement projects and examining whether effects vary with local temperature and pollution exposure.

2. Data

Our study uses unique data from New York State, which covers the 2005-06 to 2018-19 school years, to investigate the relation between school building HVAC systems and student absenteeism, behavior, and learning. In particular, we extract data from the New York Building Conditions Surveys (BCS)[2] reports in 2005, 2010, and 2015 to learn about school building conditions over time, including cooling, heating, and ventilation systems. Additionally, we use retrospective questions from the 2005, 2010, 2015, 2020, 2021, and 2022 BCS reports to identify years in which HVAC system reconstruction or replacement occurred, through the 2018–19 school year.[3] We use the school-specific survey year and month in each report to match with school years (see Appendix Figure A1). Each report provides an inspection of the conditions of one of approximately 4,300 buildings in school districts outside of New York City. We exclude approximately 1,100 district buildings that are not used for instructional purposes and approximately 400 buildings that are secondary instructional buildings or do not clearly match schools in the education data.[4] Our final sample retains 2,855 unique school buildings from 2005-06 to 2018-19, with 2,835 schools containing non-missing HVAC system conditions

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[2] New York regulations treat the BCS as the more comprehensive school-facility assessment. Unlike a Visual Inspection, the BCS must be conducted at least every five years by a team that includes a licensed architect or engineer and must evaluate all major building systems and environmental conditions. NYSED guidance further requires detailed, professionally certified documentation and allows specialized engineering tests, supporting the treatment of the BCS as a more technically rigorous measure of building condition.
[3] Not all schools were surveyed in the exact survey years and school years can vary within calendar years. Since 2020, the New York State Education Department changed its practice of collecting BCS data to survey approximately 20% of school districts each year instead of surveying all districts every five years. We therefore only observe reconstructions and replacements after 2015 for approximately three-fifths of the school districts in the sample.
[4] When a school has multiple identified instructional buildings, we use the oldest one, as it is more likely to be the primary instructional building.

information, 2,772 schools with non-missing behavioral outcome measures (including high schools) and 2,332 schools with non-missing achievement measures (limited to schools serving any grades three through eight).

We use six main questions from the BCS questionnaire: the overall conditions of cooling, heating, and ventilation systems and the most recent replacement or reconstruction years of each of these systems. The overall conditions of cooling, heating, and ventilation systems are rated in five grades in order of Excellent, Satisfactory, Unsatisfactory, Non-functional, and Critical Failure based on specific guidelines (see Appendix Table A1). Of school cooling systems in our sample, 10.9 percent are rated non-functional (or non-existent), 4.6 percent are rated unsatisfactory, 78.7 percent are rated satisfactory, and 5.8 percent are rated excellent (Appendix Table A2). Of school heating systems, 0.7 percent are rated non-functional (or non-existent), 6.2 percent unsatisfactory, 81.9 percent satisfactory, and 11.2 percent excellent. Of school ventilation systems, 1.9 percent are rated non-functional (or non-existent), 12.2 percent unsatisfactory, 81.2 percent satisfactory, and 4.7 percent excellent. Since relatively few buildings received the lowest two grades or the highest grade, we combined categories such that each HVAC system is rated either as unsatisfactory (non-existent, non-functional, or unsatisfactory) or satisfactory (satisfactory or excellent).

In using BCS survey reports, we impute data values using the most recent survey for non-survey years. This imputation assumes that the overall conditions of cooling, heating, and ventilation systems remain consistent between surveys. This assumption is imperfect, but any unobserved changes in HVAC system condition between survey years would likely introduce measurement error and attenuate the estimated effects. (We conduct a sensitivity analysis in which we restrict the sample to only years for which student outcomes are measured in the same year as the survey year, described in the robustness tests section of the paper.)

We link these condition and replacement measures to four school-level educational outcomes: (1) absenteeism rates; (2) suspension rates; (3) standardized math scores; and (4) standardized reading scores. We expect that poor conditions of HVAC systems could harm student health, comfort, or attention, and in doing so increase the likelihood of student absenteeism, worsen student behavior, and/or distract from student learning. The New York State Education Department (NYSED) provides a School Report Card that contains various annual accountability measures. Student absenteeism rates are calculated by subtracting the percent of school days in attendance of all grade levels at the school from 100 percent. Suspension rates are calculated as the number of students of any grade level receiving at least one full-day of an out-of-school suspension per 100 students.[5] Reading and math test scores from grades 3 to 8 are first standardized by grade, subject, and year. We then calculate weighted average school-level scores using the proportions of students in each grade in the school as weights. We also use logged student enrollment, the student-teacher ratio, free and reduced-price lunch student ratio, and racial/ethnic minority student group ratios (Black, Hispanic, Asian, Native American, and Multiracial) from the School Report Card as control variables.

Additionally, we calculate counts of the number of hot (over 30 degrees Celsius) days from May through September, excluding July and August to account for summer break, and the number of cold (under 0 degrees Celsius) days from November through February during the school year based on daily temperature data from the nearest station, obtained from the National

[5] Because of some observed reporting inconsistencies in suspensions, where a small number of schools would report extreme jumps in suspension rates across years (e.g. 0% to 90%), we excluded any schools where the within-school variance of the suspension rate was above the 99th percentile, and made the same exclusion for the absenteeism rate.

Climate Data Center.[6] We also extract air pollution data from NASA's Socioeconomic Data and Applications Center to calculate average PM 2.5 air pollution (particulate matter under 2.5 micrometers) at the nearest measurement site. These data allow us to assess heterogeneous effects of HVAC conditions and reconstructions/replacements by the school's local environmental conditions.

Since the lists of schools in both the BCS and with non-missing variables from the School Report Card are not perfectly consistent over the years, our final dataset is an unbalanced panel of 2,855 schools with 33,778 school-year observations.[7] We report descriptive statistics on the full sample in Table 1 and an enrollment-weighted version of these descriptives in Appendix Table A3. Of note, the average school in our sample has an absenteeism rate of 5.1 percent of school days, suspension rate of 3.2 suspensions per 100 students, and test scores 0.04 standard deviations above the state mean. 85 percent of schools in any given year have satisfactory or better cooling system conditions, 93 percent satisfactory or better heating system conditions, and 86 percent satisfactory or better ventilation system conditions. Average building construction year is 1954, with most school buildings being built either between 1920 and 1940 or between 1950 and 1975 (Appendix Figure A2). 56 percent of our sample is elementary schools, 17 percent middle schools, 21 percent high schools, and 5 percent other grade configurations. The majority of schools are located in non-urban settings: 48 percent in suburbs, 24 percent in rural locales, 12 percent in towns, and 9 percent in cities. 72 percent of students in our sample are White, 10 percent Black, 12 percent Hispanic, 4 percent Asian, and 2 percent multiracial. In

[6] This data was obtained using the R package rnoaa.

[7] 96% of the schools in our sample have all 14 years observed from the NYSED School Report Card data, but only 77% of the schools in our sample have 14 years of building conditions data available and most of the remaining schools have 9 or 10 years available, indicating they are missing a single building condition survey.

general, our sample closely mirrors demographics from the state of New York outside of New York City.[8]

3. Empirical Strategy

In this study, we seek to make use of within-school variation over time in building conditions to estimate effects of these physical changes on student absenteeism, behavior, and learning. This variation can generally come from one of two sources. First, we can observe regular deterioration of the condition of school HVAC systems over time, sometimes even leading an HVAC system to become non-functional or go into critical failure. Second, we can observe HVAC system reconstructions and replacements, which theoretically should improve the condition of the system. Over the fourteen years of our study period, these changes to HVAC system conditions occur with relatively high frequency. As shown in Appendix Table A4, building inspections document noticeable cooling system deterioration sometime between 2006 and 2019 in 380 schools and cooling system improvements in 559 schools. Over the same period, they document heating system deterioration in 329 schools, and heating system improvements in 384 schools. Finally, the building inspections document ventilation system deterioration in 428 schools and improvement in 509 schools. There are also some schools that experience both system deterioration and system improvement at different points during the period.

Our main analysis estimates effects of these changes in school building HVAC system conditions through the following model:

$$Y_{it} = \beta_0 + C'_{it}\beta_1 + X'_{it}\beta_2 + \gamma_i + \delta_t + \varepsilon_{it} \tag{1}$$

[8] The share of students in urban settings and the share of racially diverse schools may seem low given the number of cities in upstate New York. These values (urban locale, suburban locale, racial diversity) increase when we calculate student-weighted summary statistics of our sample of schools, presented in Appendix Table A3.

In this equation, Y_{it} represents student outcomes for school *i* in year *t*, C_{it} is a vector of indicators representing the condition of a heating, cooling, and ventilation systems at school i in year t, and X_{it} represents time-varying covariates, including logged student enrollment, pupil-to-teacher ratio, and ratio of students by free lunch eligibility and race/ethnicity categories. We include school fixed effects (γ_i) to account for all time-invariant characteristics of schools and year fixed effects (δ_t) to account for all common time trends. Standard errors are clustered at the school level to account for serial correlation. We use OLS estimation for the continuous test score outcomes and Poisson estimation for the skewed count outcomes of absence and suspension (see Appendix Figure A3), because OLS can be biased in such cases due to heteroskedasticity and overweighting of extreme values (Silva & Tenreyo, 2006; Cameron & Trivedi, 2013; Wooldridge, 2002).

For β_1 to produce an unbiased estimate of the causal effect of HVAC condition changes on student outcomes, three main assumptions must hold. First, schools whose HVAC conditions changed in a BCS year would have followed the same outcome trajectory as schools whose conditions did not change, absent the change. Although the parallel trends assumption itself is untestable, we test for parallel pre-treatment outcome trends between schools that experienced condition changes and those that did not. We fail to reject the null that all pre-period coefficients are jointly zero for 11 of 12 system-outcome combinations for improvement events and all 12 of the 12 for deterioration events, providing some support for this assumption.[9] Second, nothing else changed at the school level concurrently with the HVAC condition change in a way that

[9] Specifically, we estimate event study regressions using cooling, heating, and ventilation system first school improvements and first school deteriorations in survey years for all four outcomes and conduct joint F-tests on the pre-period coefficients. The only test out of 24 that failed was for the suspension rate and heating system improvements. The estimated effects of satisfactory heating system condition on student suspension rates should therefore be interpreted with caution.

independently affects student outcomes. Results are robust to accounting for co-occurring major renovations and construction and to including district-by-year fixed effects, although these checks cannot rule out unobserved school-specific time-varying confounders. Third, the BCS condition rating must be a valid measure of actual physical system condition rather than a reflection of school or student characteristics. The requirement that licensed architects or engineers conduct assessments following systematic rating guidelines supports this interpretation (see Appendix Table A1), though the ratings may still contain measurement error.

The condition analysis captures both deterioration and improvement, but it does not identify the specific projects responsible for those changes. We therefore conduct a second analysis using the reported timing of major reconstructions and replacements. For each HVAC system, the Building Conditions Survey records the year of the most recent reconstruction or replacement, allowing us to estimate how student outcomes change following these projects. Between 2006 and 2019, we observe 1,283 cooling system projects, 1,273 heating system projects, and 1,323 ventilation system projects across the schools in our sample.

There are two primary sources of bias in two-way fixed effects estimation for this type of difference-in-differences design. The first source of bias arises from parallel trends assumption violations, which are common in practice (Chiu et al., 2023; Rambachan & Roth, 2023). The second source of bias arises when treatment timing is staggered and there are heterogeneous treatment effects across groups or over time (Goodman-Bacon, 2021). To avoid the empirical issues associated with two-way fixed effects under staggered adoption, we instead opt for the Callaway and Sant'Anna doubly robust difference-in-differences estimator (Callaway & Sant'Anna, 2021; Sant'Anna & Zhao, 2020). This method relies on a weighted average of estimates of the average treatment effect on the treated using only "clean comparisons" of treated units with never treated units or not-yet-treated units. The estimator also uses inverse probability weighting based on baseline covariates to improve comparability between treatment and control groups. We present event study estimates to assess pre-treatment trends and to show how the impacts of HVAC system replacement or reconstruction on student outcomes evolve over time.

4. Results

4.1. Exposure to Poor HVAC System Conditions

We begin with a descriptive analysis of how HVAC system conditions vary across student populations. Figure 1 presents students' exposure to unsatisfactory school-reported indoor air quality, overall building condition, and cooling, heating, and ventilation systems by economic status in panel (a) and by race and ethnicity in panel (b). Cooling system conditions are generally similar across student groups, with approximately 15 percent of students attending schools with unsatisfactory or nonfunctional cooling systems. Larger disparities emerge for heating and ventilation systems. About 7 percent of White students attend schools with inadequate heating systems, compared with 10 percent of Black and Hispanic students. Students eligible for free or reduced-price lunch are also somewhat more likely than other students to attend schools with inadequate heating.

Disparities in ventilation system conditions are larger. Approximately 16 percent of students eligible for free or reduced-price lunch attend schools with inadequate ventilation systems, compared with 14 percent of students who are not eligible. Similarly, about 18 percent of Black and Hispanic students attend schools with inadequate ventilation, compared with approximately 13 percent of White and Asian students. Clear income- and race-based disparities also appear in inspection ratings of indoor air quality and overall building condition. These patterns suggest that any adverse effects of poor HVAC conditions on student attendance, learning, or behavior may be disproportionately borne by lower-income, Black, and Hispanic students in New York.

The consequences of HVAC system conditions may also vary with the environmental context surrounding the school. For example, nonfunctioning cooling systems may matter more in hotter regions of the state, nonfunctioning heating systems may matter more in colder regions, and inadequate ventilation systems may matter more in areas with higher levels of air pollution. Appendix Figures A4 through A6 examine the environmental conditions surrounding schools with unsatisfactory HVAC systems in the most recent year of our data, 2019.

Appendix Figure A4 shows that schools with unsatisfactory cooling systems are distributed across the state, including many in downstate regions that experienced a relatively large number of hot days in 2019. Appendix Figure A5 shows that schools with unsatisfactory heating systems are concentrated primarily in the coldest upstate regions. Finally, Appendix Figure A6 shows that schools with inadequate ventilation systems are concentrated in urban areas, including the New York City suburbs and Buffalo, where PM2.5 pollution levels are relatively high. These patterns suggest that nonfunctional HVAC systems may have important consequences for student health, comfort, and concentration given the environmental conditions surrounding the affected schools.

4.2. Effects of HVAC System Condition Changes on Student Outcomes

We first examine the effects of changes in cooling, heating, and ventilation system conditions on student absenteeism and suspensions. Table 2 presents the results from separate two-way fixed-effects regressions for each HVAC system type. The coefficients on satisfactory system condition represent the estimated difference between systems rated satisfactory or excellent and systems rated unsatisfactory, nonfunctional, or nonexistent. Because the absence and suspension models are estimated using Poisson regression, the reported coefficients represent changes in the log of the expected outcome rate when a system moves from unsatisfactory to satisfactory condition. In the text, we translate these coefficients into percentage changes.

Column 1 shows that student absences are 1.7 percent lower when cooling systems are in satisfactory rather than unsatisfactory condition ($p < 0.1$), 2.9 percent lower when heating systems are in satisfactory condition ($p < 0.05$), and 1.7 percent lower when ventilation systems are in satisfactory condition ($p < 0.1$). Column 2 shows a similar pattern for student suspensions. Suspensions are 2.3 percent lower when cooling systems are in satisfactory rather than unsatisfactory condition ($p < 0.1$), 3.6 percent lower when heating systems are in satisfactory condition ($p < 0.05$), and 6.2 percent lower when ventilation systems are in satisfactory condition ($p < 0.01$). Overall, within-school changes in HVAC system conditions indicate that satisfactory conditions reduce both student absences and suspensions relative to unsatisfactory conditions.

Columns 3 and 4 of Table 2 present the corresponding estimates for student achievement in reading and math. Across cooling, heating, and ventilation systems, students score approximately 0.015 to 0.03 standard deviations higher in reading when systems are in satisfactory or excellent condition rather than unsatisfactory or nonfunctional condition. Only the cooling system estimate, however, is statistically significant, at 0.029 standard deviations ($p < 0.05$).

For math, students score approximately 0.03 standard deviations higher under satisfactory ventilation system conditions, an estimate that is marginally significant ($p < 0.1$), and approximately 0.05 standard deviations higher under satisfactory heating system conditions ($p <$

0.05). Changes in cooling system conditions, by contrast, have no significant effect on math scores. Although these effects are modest in magnitude, corresponding to approximately one-tenth of average annual test-score gains (Hill et al., 2007), they provide evidence that HVAC system conditions contribute to the quality of the school learning environment. The comparatively stronger heating effects may partly reflect New York's climate, in which schools experience many more cold days than extremely hot days, making reliable heating more consistently important than cooling across the school year.

4.3. Effects of HVAC System Reconstructions or Replacements on Student Outcomes

The changes in school HVAC system conditions that we observe between 2006 and 2019, summarized descriptively in Appendix Table A4, could result either from system deterioration over time or from system upgrades and replacements. The Building Conditions Survey provides information on the date of the most recent cooling, heating, and ventilation system reconstruction or replacement. As described in the methods section, we use these dates to estimate the effects of HVAC system reconstructions and replacements on school and student outcomes using a modified difference-in-differences approach. The results are presented in Table 3.

Beginning with cooling system reconstructions and replacements, we find no significant effects on student absence, suspension, or reading scores. We do, however, observe a 0.034 standard deviation increase in math scores following cooling system replacement. This finding is consistent with prior evidence that air conditioning can protect students from the adverse effects of heat on learning (Park et al., 2020). A similar pattern emerges for heating system reconstructions and replacements. Heating system reconstruction or replacement has no significant effect on absence, suspension, or reading scores, but it increases math scores by 0.039 standard deviations. Ventilation system reconstructions and replacements may reduce student absenteeism by 0.072 percentage points—about 1.4 percent relative to the sample mean absence rate of 5.1 percent—although this estimate is only marginally significant ($p < 0.1$), and have no average effect on the other academic or behavioral outcomes.

One reason for these relatively limited effects may be that most projects did not follow an observed unsatisfactory system rating. Among projects for which a preceding BCS condition rating could be identified, only 13.4% of cooling projects, 7.8% of heating projects, and 15.3% of ventilation projects followed an unsatisfactory rating. Most observed projects therefore appear to have involved maintenance or modernization of already-functioning systems rather than remediation of clearly inadequate conditions. Despite the relatively small share of projects following an unsatisfactory rating, reconstructions and replacements generally improved the corresponding system-condition ratings (Appendix Figure A8).

We present full CSDID event-study estimates for behavioral outcomes in Figure 3 and achievement outcomes in Figure 4, covering the eight years before and eight years after HVAC system replacement. In general, neither behavioral nor academic outcomes appear to trend systematically upward or downward before an HVAC system reconstruction or replacement. Most outcomes also remain relatively flat after treatment. Focusing on the math-score results in Figure 4, trends were fairly stable for at least six years before cooling and heating system replacement and then increased following replacement. The positive effects of HVAC system reconstruction or replacement on math scores do not appear immediately, but instead emerge after several years, perhaps in part because of the short-term disruption associated with school renovation.

4.4 Heterogeneity

There are several reasons to examine whether the effects of HVAC system conditions, reconstructions, and replacements vary across students, schools, and environmental contexts. First, we seek to understand the equity implications of the relationship between HVAC systems and learning, and therefore examine effects separately for schools serving larger and smaller shares of students of color and low-income students. Second, we examine whether external environmental conditions moderate the effects of HVAC systems on student outcomes. We hypothesize, for example, that schools in areas with more extreme temperatures may benefit more from effective cooling and heating systems, while schools in areas with higher air pollution may benefit more from effective ventilation. Third, we test whether schools with unsatisfactory HVAC systems benefit more from reconstruction or replacement than schools whose systems were already in satisfactory condition before the event.

Focusing first on HVAC system conditions, Figure 2 presents heterogeneous effects of satisfactory system conditions by system type and school type for each of the four outcomes: (a) absences, (b) suspensions, (c) reading scores, and (d) math scores. The corresponding regression estimates are reported in Appendix Tables A6, A7, and A8. We also formally test whether the estimated effects differ across school groups, as reported in these tables. Several of the differences described below are statistically significant, while others represent meaningful differences in point estimates that are not statistically distinguishable.

For student absenteeism, effects are generally similar across school types, with one notable exception. Reductions associated with satisfactory heating system conditions are larger in secondary schools, where absenteeism declines by 4.1 percent ($p < 0.05$), than in primary schools, where the estimated 1.4 percent reduction is not statistically significant. Heating effects are also larger in schools serving more students of color, defined as schools with less than 70 percent White enrollment, where absenteeism declines by 4.5 percent ($p < 0.05$), compared with a statistically insignificant 2.0 percent reduction in schools serving fewer students of color. Similarly, absenteeism decreases by 4.6 percent in high-poverty schools, defined as schools with more than 50 percent of students eligible for free or reduced-price lunch ($p < 0.05$), compared with a statistically insignificant 1.6 percent decrease in the remaining schools. We find no notable differences in absenteeism effects across school types for cooling or ventilation system conditions.

For student suspensions, the benefits of satisfactory cooling system conditions are most evident in primary schools, where suspensions decrease by 5.6 percent ($p < 0.05$). For heating, the greatest reduction occurs in schools serving fewer students of color, at 5.6 percent ($p < 0.01$). The suspension effects of satisfactory ventilation systems are concentrated more heavily in schools serving more students of color, where suspensions decline by 9.2 percent ($p < 0.01$), a statistically significant difference from the estimate for schools serving fewer students of color. High-poverty schools also experience a sizeable reduction of 9.9 percent ($p < 0.01$).

For test-score outcomes, satisfactory cooling system conditions yield substantially greater gains in schools serving more students of color, increasing reading scores by 0.071 standard deviations ($p < 0.01$) and math scores by 0.047 standard deviations ($p < 0.1$). The difference in reading effects by school racial composition is statistically significant. Cooling-related reading gains are also more pronounced in high-poverty schools, at 0.062 standard deviations ($p < 0.05$). Heating follows a similar pattern: in schools serving more students of color, satisfactory conditions increase reading scores by 0.067 standard deviations ($p < 0.1$) and math scores by 0.100 standard deviations ($p < 0.01$). Estimated gains in high-poverty schools are around 0.07 standard deviations in both reading and math, although they are only marginally significant in these smaller subgroup samples. For ventilation, the most favorable achievement estimates again occur in schools serving more students of color, with increases of 0.064 standard deviations in reading ($p < 0.05$) and 0.067 standard deviations in math ($p < 0.05$); the difference in reading effects by racial composition is marginally significant ($p = 0.053$). The ventilation effect on reading is also particularly pronounced in high-poverty schools, at 0.084 standard deviations ($p < 0.01$), and differs significantly from the corresponding effect in lower-poverty schools.

The main takeaway from these regressions is that HVAC system conditions appear to matter more in schools serving larger shares of students of color and low-income students, particularly for achievement outcomes. Although not every difference across groups is statistically distinguishable, the pattern of larger point estimates in these schools is consistent across several outcomes and system types. One possible explanation is that schools in wealthier districts have access to additional protective resources. For example, they may be better able to install portable air filters or temporary air-conditioning units when central HVAC systems malfunction. Another possibility is that schools serving these student populations differ in environmental or climate-related characteristics that make them more sensitive to changes in HVAC system conditions. We examine these possibilities in an additional set of regressions.

Appendix Figure A7 presents the effects of satisfactory heating, cooling, and ventilation system conditions by environmental characteristics. Specifically, we examine schools experiencing a large number of hot days, defined as days above 30 degrees Celsius during the school year; a large number of cold days, defined as days below 0 degrees Celsius; and high average PM2.5 air pollution at nearby monitoring stations. We find few large differences across environmental groups for the behavioral outcomes shown in panels (a) and (b), although satisfactory heating system conditions significantly reduce absenteeism in high-pollution areas.

The differences are much larger for test-score outcomes, shown in panels (c) and (d). For all three HVAC system types, positive effects on reading and math scores are systematically much larger in high-pollution regions, and the differences in reading effects by pollution level are statistically significant across all three system types. This pattern provides strong support for air quality as one potential mechanism through which HVAC system conditions improve student outcomes.

There is some overlap between high-pollution schools and the other school groups for which we estimate larger effects, but the overlap is not complete. Only 53 percent of high-pollution schools serve larger shares of students of color, and 32 percent are high-poverty schools. Some high-pollution regions are located in lower-income urban areas, including Buffalo and parts of Long Island, while others are located in wealthier New York City suburbs (Appendix Figure A6).

We also explore whether school environment and climate moderate the effects of HVAC system reconstructions and replacements in Appendix Table A9. As in the system-condition regressions, regional temperature appears to play only a limited role. The positive effect of heating system events on math scores is somewhat larger in cold regions than in hot regions, with an estimated effect of 0.037 standard deviations ($p < 0.1$), compared with 0.010 standard deviations. The clearest evidence of heterogeneity, however, appears across areas with different levels of air pollution. The positive effect of cooling system reconstruction or replacement on math scores is 0.056 standard deviations in high-pollution areas ($p < 0.05$) and essentially zero in low-pollution areas (0.005 standard deviations). Similarly, the positive effect of heating system reconstruction or replacement on math scores is 0.065 standard deviations in high-pollution areas

($p < 0.01$) and 0.015 standard deviations in low-pollution areas. We discuss the implications of these findings for potential mechanisms in the following section.

When we restrict HVAC system reconstructions and replacements to those occurring after an unsatisfactory system rating, the number of qualifying events declines substantially. The resulting estimates are imprecise and are sometimes more positive. For example, the estimated effect of replacing an unsatisfactory cooling system is 0.23 standard deviations, although it is not statistically significant. This pattern does not hold consistently across outcomes or systems, however. We are therefore unable to determine whether pre-replacement system condition meaningfully moderates the effects of HVAC system reconstruction or replacement.

4.5 Mechanisms

The estimated relationships among within-school changes in HVAC conditions, HVAC system reconstructions and replacements, and student outcomes could operate through several mechanisms. First, improvements in school HVAC system conditions could reduce the spread of infectious disease within schools (Lindsley et al., 2021), thereby reducing absences due to illness. Second, improvements in heating or cooling system conditions could improve temperature control and create a more comfortable environment for learning (Park et al., 2020). More comfortable indoor temperatures could also reduce student misbehavior, given the well-established relationship between heat and criminal behavior (Cohen & Gonzalez, 2024). Third, improved HVAC systems could enhance indoor air quality, mitigating the harmful effects of poor air quality on student health and learning (Ebenstein et al., 2016; Gilraine, 2025; Persico & Venator, 2021).

Because we cannot observe actual disease transmission or temperature changes within schools, we cannot directly test the first two mechanisms. We do, however, observe a subjective measure of indoor air quality from the building inspections. Appendix Table A5 shows that changes in HVAC system conditions are associated with clear improvements in indoor air quality ratings. Satisfactory cooling system conditions increase the likelihood of receiving a fair or good air quality rating by 7 percentage points, satisfactory heating system conditions increase this likelihood by 10 percentage points, and satisfactory ventilation system conditions increase it by 12 percentage points. These improvements reflect both fewer poor air quality ratings, shown in Appendix Table A5, column 2, and shifts from fair to good ratings, shown in columns 3 and 4. HVAC system reconstructions and replacements also significantly increase the likelihood of a satisfactory indoor air quality rating (Appendix Figure A8).

These findings should be interpreted cautiously because building inspectors are not required to conduct scientific measurements of indoor air quality. Inspectors may report improved air quality because they are aware of a recent system replacement or because they assessed the HVAC system favorably in the same inspection report. Even so, the results suggest that indoor air quality may mediate at least part of the relationship between HVAC system improvements and student outcomes.

The heterogeneity analyses described above and presented in Appendix Figure A7 and Appendix Table A9 provide additional support for an air quality mechanism. The positive associations between satisfactory cooling, heating, and ventilation system conditions and student outcomes are concentrated almost entirely among schools in high-pollution areas. Similarly, the positive achievement effects of HVAC system reconstructions and replacements are concentrated among events occurring in high-pollution areas. Given the established causal relationship between air pollution and student achievement (Nguyen, 2026), as well as evidence from prior interventions designed to improve air quality in schools and school buses (Austin, 2019;

Gilraine, 2025; Stafford, 2015), our findings provide additional evidence that air quality is an important determinant of student learning.

4.6. Robustness Tests

We conduct several sensitivity tests to assess the robustness of our main findings. First, as noted in the discussion of the assumptions underlying our two-way fixed-effects analysis, we seek to ensure that changes in HVAC system conditions are not preceded by, or themselves producing, other changes in the school environment. In Appendix Table A10, we estimate the effects of satisfactory HVAC system conditions on several school covariates: the percentage of students eligible for free or reduced-price lunch in column 1, the percentage of students who are non-White in column 2, the school pupil-to-teacher ratio in column 3, and school enrollment in column 4. These outcomes capture observable changes in student demographics and income, school resources as reflected in staffing levels, and school size.

Across these 12 regressions with school and year fixed effects, we find no effects of satisfactory cooling, heating, or ventilation system conditions on these time-varying school covariates at the 5 percent significance level. Two estimates are marginally significant: satisfactory cooling system conditions are associated with a 0.0035 increase in the proportion of students who are non-White ($p < 0.1$), and satisfactory ventilation system conditions are associated with a 0.0097 increase in log enrollment ($p < 0.1$). These coefficients are small and no more numerous than might be expected by chance. We are therefore more confident that the observed academic and behavioral effects of HVAC system conditions do not simply reflect other underlying changes occurring within schools.

We also estimate several alternative specifications of HVAC system condition. These include entering all three systems in the same regression (Appendix Table A11); estimating the effects of having any system or all systems in satisfactory condition (Appendix Table A12); distinguishing between satisfactory and excellent HVAC system conditions (Appendix Table A13); and separately estimating the effects of system improvements and deteriorations (Appendix Table A14). The conditions of the three HVAC systems are correlated, and this is reflected in the alternative specifications. Even so, both "any system satisfactory" and "all systems satisfactory" are associated with significant reductions in student suspensions and increases in reading and math scores. "Any system satisfactory" is also associated with lower student absenteeism.

We also find that coefficients for systems in excellent condition are generally larger than those for systems in satisfactory condition, suggesting an approximately monotonic relationship between HVAC system condition and student outcomes. Both system improvements and deteriorations contribute to the main findings. HVAC system deterioration is particularly associated with increases in student suspensions, while system improvements are more strongly associated with gains in achievement. This pattern may help explain why the estimated effects of HVAC system reconstructions and replacements are more concentrated among test-score outcomes than behavioral outcomes.

For the Callaway and Sant'Anna (2021) estimates of HVAC system reconstructions and replacements, we conduct two additional robustness tests, presented in Appendix Table A15. First, we restrict the comparison group to never-treated schools rather than including all not-yet-treated schools. In this context, never-treated schools are those that do not experience replacement of the relevant system between 2007 and 2019. Under this restriction, cooling system replacements continue to increase math scores by 0.037 standard deviations ($p < 0.05$), and heating system replacements increase math scores by 0.041 standard deviations ($p < 0.01$).

Second, we exclude HVAC system events that occur within the same two-year period as a major schoolwide renovation (panel (b) of Appendix Table A15). This restriction removes one of the most plausible simultaneous events that could confound the estimated effect of an HVAC system reconstruction or replacement. Heating system replacements continue to increase math achievement by 0.038 standard deviations ($p < 0.05$). The estimated effect of cooling system replacement remains positive, at 0.023 standard deviations, but is no longer statistically significant. Once major renovations are excluded, we also find that ventilation system events reduce student absenteeism by 0.096 percentage points, or about 1.9 percent relative to the sample mean ($p < 0.05$). Overall, the reconstruction and replacement findings are relatively robust to these alternative specifications.

Appendix Table A16 presents an additional set of sensitivity checks for the HVAC system-condition regressions, several of which are described elsewhere in the paper. Column 1 reports estimates without covariates. Column 2 includes the standard covariates along with controls for major school renovation and district capital outlay spending on construction. Column 3 restricts the sample to Building Conditions Survey years. Column 4 restricts the analysis to schools observed in a fully balanced panel. Column 5 applies analytical weights based on school enrollment. Column 6 adds district-by-year fixed effects. Column 7 reports estimates from the de Chaisemartin and D'Haultfoeuille (2026) dynamic difference-in-differences estimator. This estimator addresses concerns related to staggered treatment timing and heterogeneous treatment effects while also permitting treatment status to increase or decrease multiple times, as occurs with changes in HVAC system conditions. These robustness tests address several data limitations and potential sources of endogeneity, including school renovations and time-varying district-level confounders.

Overall, the robustness checks largely preserve the direction and general magnitude of the main estimates, although statistical precision varies across specifications. For absences, the estimates remain negative for all three HVAC systems in every specification. The effects of satisfactory cooling system conditions are at least marginally significant in six of the seven robustness checks, while heating system effects are at least marginally significant in five of the seven. The suspension results provide especially strong and consistent evidence for ventilation systems. The estimates remain negative, similar in magnitude to the main estimate of -0.064, and statistically significant across all specifications except the de Chaisemartin and D'Haultfoeuille estimator. That estimator relies on a substantially smaller sample and cannot accommodate the skewed distribution of the behavioral outcomes through Poisson regression, which may help explain the imprecision of its estimates, although the point estimates remain large and negative.

For reading achievement, the positive cooling system estimate is also relatively robust. Estimates remain positive across all specifications and are generally similar to the main estimate of 0.029 standard deviations, although they are not always statistically significant in the smaller samples. Heating and ventilation estimates are also generally positive, but are smaller and less precisely estimated across specifications.

The most robust achievement result is the positive association between satisfactory heating systems and math performance. The estimates remain positive and statistically significant in every specification, ranging from 0.042 to 0.110 standard deviations. Ventilation estimates for math are also generally positive and often statistically significant. In contrast, cooling system estimates for math are small and statistically insignificant in nearly all specifications, with the exception of the student-weighted model.

5. Returns on HVAC System Improvements

Considering competing priorities for school spending, the extent to which the benefits of HVAC system upgrades justify their costs is an important consideration for decision-making. One way to put these potential benefits in perspective is to compare the achievement gains from HVAC improvements with those generated by other educational investments. Jackson and Mackevicius (2024) estimate that an additional $1,000 in per-pupil spending per year, sustained over four years, increases test scores by 0.0316 standard deviations. Using this estimate as a benchmark, we conduct a back-of-the-envelope cost-effectiveness analysis focusing on an improvement in heating system condition from unsatisfactory to satisfactory. Our estimates indicate that satisfactory heating system conditions increase math achievement by 0.0462 standard deviations. A test-score gain of this magnitude is comparable to that generated by about $1,460 in additional per-pupil spending annually over four years. By comparison, the 2015 BCS data indicate that the one-time per-student cost of heating system upgrades was about $720.[10] Although this cost estimate does not capture future maintenance or operating expenses, the comparison suggests that heating system improvements may be a relatively cost-effective way to generate achievement gains.

A second benchmark helps translate these achievement gains into potential longer-run economic benefits. Using administrative tax records, Chetty, Friedman, and Rockoff (2011) estimate that a 1 standard deviation increase in test scores in a single grade raises earnings at age 28 by $1,815, or 8.9 percent, and corresponds to a discounted present value of $46,190 in lifetime earnings. Applying this benchmark to our estimated 0.0462 standard deviation math effect implies a present value of $2,130 in higher lifetime earnings per student, compared with

[10] The per-pupil cost estimates were calculated using school buildings that reported both the cost of a heating system upgrade and the number of students using the building, regardless of their prior heating-system condition. In addition, the top and bottom 5 percent of cost values were excluded to reduce the influence of possible input errors and outliers from buildings with very small numbers of students.

the $720 one-time upgrade cost. This calculation is illustrative: the Chetty et al. estimates come from a different population and intervention, are expressed in 2010 dollars, and pertain to achievement gains in a single grade. Even so, they provide an additional indication that modest improvements in achievement can generate economically consequential long-term benefits.

System upgrades may also generate benefits by reducing disparities in exposure to poor building conditions. In the 2015-16 school year, 7.6 percent of minority students and 5.9 percent of White students attended schools with unsatisfactory heating systems. As shown in Appendix Table A7, the estimated effects of heating system condition are concentrated largely in schools we classify as high-minority, defined as schools with less than 70 percent White enrollment. In 2015-16, 6.3 percent of minority students and 1.7 percent of White students attended high-minority schools with unsatisfactory heating systems. Given the 0.100 standard deviation heating-system effect estimated for high-minority schools, this differential exposure corresponds to average math-score losses of 0.0063 standard deviations for minority students and 0.0017 standard deviations for White students. The resulting exposure-weighted statewide racial gap associated specifically with unsatisfactory heating systems in high-minority schools is about 0.0046 standard deviations.

Using Jackson and Mackevicius (2024) as a benchmark, eliminating this 0.0046 standard deviation gap would produce an equity gain comparable to the test-score improvement generated by roughly $145 in additional per-pupil spending annually for four years. Across roughly 500,000 students of color, this corresponds to about $73 million per year, or $291 million over four years, in spending-equivalent educational gains associated with reducing this disparity. This calculation does not represent benefits in addition to the broader achievement gains from heating-system improvements; rather, it illustrates the distributional value of directing those improvements toward reducing unequal exposure to poor heating conditions.

The Chetty et al. (2011) earnings benchmark provides a complementary perspective. A 0.0046 standard deviation reduction in this racial achievement gap corresponds to $212 in discounted lifetime earnings per student of color, or roughly $106 million across 500,000 students. These calculations should be interpreted as benchmarks rather than precise benefit estimates, but they illustrate that reducing racial disparities in exposure to poor HVAC conditions could account for a substantial portion of the economic value generated by system improvements. The total equity-related value could be larger if schools excluded from the analysis, including those in New York City, experienced similar disparities.

6. Discussion

Building conditions can influence whether students are healthy enough to attend school, comfortable enough to concentrate, and situated in environments that support teaching and learning. Consistent with this idea, recent causal studies find that investments in school buildings, ventilation, filtration, and other environmental improvements can yield educational benefits (Biasi et al., 2025; Bonan et al., 2025; Gilraine, 2025; Persico & Fuller, 2025; Stafford, 2015). Our study contributes to this literature by using repeated professional inspections to observe the physical and functional condition of school HVAC systems over time. We distinguish changes in system condition from major reconstructions and replacements and link both measures to attendance, suspensions, reading, and math outcomes.

The descriptive findings reveal inequalities in access to satisfactory school environments. Black and Hispanic students and students from low-income families are more likely to attend schools with inadequate heating and ventilation systems and poorer reported indoor air quality, consistent with national evidence that districts serving lower-income communities face greater facility deficiencies (Alexander & Lewis, 2014). These disparities are consequential because improvements in school HVAC conditions lead to lower absenteeism and suspensions and to gains in reading or math for several system types. Poor HVAC conditions therefore represent not only an infrastructure deficiency, but also a potential contributor to unequal educational opportunity.

The heterogeneity results reinforce this concern. Achievement estimates are generally greatest in schools serving larger shares of students of color and students from low-income families, while some attendance and suspension effects are also concentrated in these schools. This pattern suggests that the same system inadequacies impose greater costs in schools serving more disadvantaged populations. Schools in wealthier communities may have greater access to temporary protections, such as portable filtration or cooling equipment, and poor HVAC conditions may compound other resource constraints and environmental exposures. Inadequate systems can therefore perpetuate educational inequality: disadvantaged students are both more likely to experience poor HVAC conditions and face greater consequences when they do.

Our results provide the strongest support for indoor air quality as a primary mechanism. Satisfactory cooling, heating, and ventilation conditions improve inspectors' indoor air-quality ratings, as do major HVAC reconstructions and replacements. Achievement effects are also substantially greater in high-pollution areas, whereas we find little systematic heterogeneity by local temperature. These patterns align with causal evidence that air pollution exposure reduces student learning and school attendance (Duque & Gilraine, 2022; Heissel et al., 2022; Nguyen, 2026; Persico & Venator, 2021).

Air pollution may affect students through both health-related and neurocognitive pathways. Exposure to air pollutants can worsen respiratory health, including asthma, bronchitis, and pneumonia, and increase school absences due to respiratory illness (Beatty & Shimshack, 2011; Gilliland et al., 2001). Experimental and observational research also links air pollution to oxidative stress, systemic and neural inflammation, and changes in brain structure and cognitive performance (Block & Calderón-Garcidueñas, 2009; Calderón-Garcidueñas et al., 2008). Pollution may therefore affect learning both indirectly, by reducing students' time in school, and more directly, by interfering with cognitive functioning while students are present. Our subjective indoor air-quality measure cannot identify these pathways directly, but the consistency of the indoor-air-quality and pollution heterogeneity results makes air quality the mechanism most clearly supported by our analyses. Reduced infectious-disease transmission and improved thermal comfort remain plausible additional explanations.

The reconstruction and replacement results are positive but more limited than the system-condition results. Cooling and heating projects improve math achievement but have no average effects on the other outcomes. One explanation is that most projects do not remediate systems rated unsatisfactory or nonfunctional. Before reconstruction or replacement, 87% of cooling systems, 92% of heating systems, and 85% of ventilation systems were already rated satisfactory or excellent. Many projects may therefore represent routine or preventive replacement, capacity expansion, or energy-efficiency improvements. These investments may preserve reliability and prevent future failure without producing the immediate environmental change associated with moving an inadequate system into satisfactory condition.

The specific features of the upgrades may also help explain the contrast with more recent research. Persico and Fuller (2025) note that North Carolina HVAC upgrades undertaken before

2020 generally did not include advanced filtration, whereas many post-2020 projects added filtration specifically intended to improve indoor air quality. Our New York projects largely predate this shift and may likewise have focused more on replacing equipment than on removing airborne pollutants. We cannot test this explanation because we lack detailed project specifications, but it suggests that newer HVAC investments designed around filtration and measurable air-quality improvements could produce clearer benefits than the broader set of earlier projects in our sample.

The heterogeneity findings point to a related targeting issue. Educational benefits are greatest in many high-pollution, high-minority, and high-poverty schools, yet projects are not consistently concentrated in these settings or in schools with unsatisfactory systems. The average replacement effects may therefore combine projects that substantially improve students' environments with projects that primarily maintain already-functioning equipment. This interpretation is consistent with prior research showing that interventions aimed directly at improving air quality or addressing identified facility problems can produce clearer educational benefits (Gilraine, 2025; Persico & Fuller, 2025; Stafford, 2015). It also aligns with evidence that environmentally focused capital investments generate larger returns in disadvantaged communities (Biasi et al., 2025).

Several limitations qualify these conclusions. Inspections were not conducted annually, requiring us to carry condition ratings forward between surveys, although results are similar when restricted to survey years. System-condition and indoor air-quality ratings also rely on professional judgment rather than objective environmental measurements. Finally, we lack detailed information on project components and student-level health and exposure. Future research could link project specifications and classroom measures of temperature, particulate matter, humidity, and ventilation rates to student health and educational outcomes. Such data would help distinguish routine replacement from projects that materially improve the conditions students experience.

The policy implications are nonetheless encouraging. Satisfactory HVAC systems support attendance, behavior, and achievement, and the back-of-the-envelope cost-benefit analysis suggests that these gains can compare favorably with project costs. The estimated math effect of satisfactory heating conditions corresponds to a present value of about $2,130 in higher lifetime earnings per student, compared with a reported one-time heating project cost of approximately $720 per student. These calculations are not comprehensive, but they indicate that HVAC improvements can represent worthwhile educational investments.

The findings also suggest how states and districts could increase the returns to HVAC investments. Regular professional assessments can identify deteriorating systems before failure and support timely maintenance and replacement.[11] These assessments can also help prioritize schools where poor system condition coincides with high pollution exposure and substantial student need. State capital funding can reinforce this approach by directing greater resources toward districts with weaker local tax bases and greater facility needs. This is particularly relevant in New York, where local property-tax differences contribute to racial disparities in building conditions and progressive state building aid helps offset them (Ambali et al., 2026).

The policy implications are therefore twofold. Continued investment in school HVAC systems is worthwhile because satisfactory conditions can improve attendance, behavior, and

[11] Engineering evidence suggests that HVAC systems generally deteriorate progressively over their service lives rather than remaining near new condition until sudden failure. Frank et al. (2023) document an approximately linear decline across a substantial range of HVAC component condition, while De Silva et al. (2022) show that deterioration rates vary with system runtime, operating intensity, and maintenance practices. Regular assessment and preventive maintenance may therefore slow accumulated performance losses and help districts identify systems requiring repair or replacement before failure.

achievement. Those investments should also be targeted carefully toward inadequate systems and schools facing greater environmental, fiscal, and socioeconomic disadvantages. Combining adequate funding with preventive maintenance, modern filtration, and equitable allocation could strengthen school infrastructure while increasing its educational benefits.

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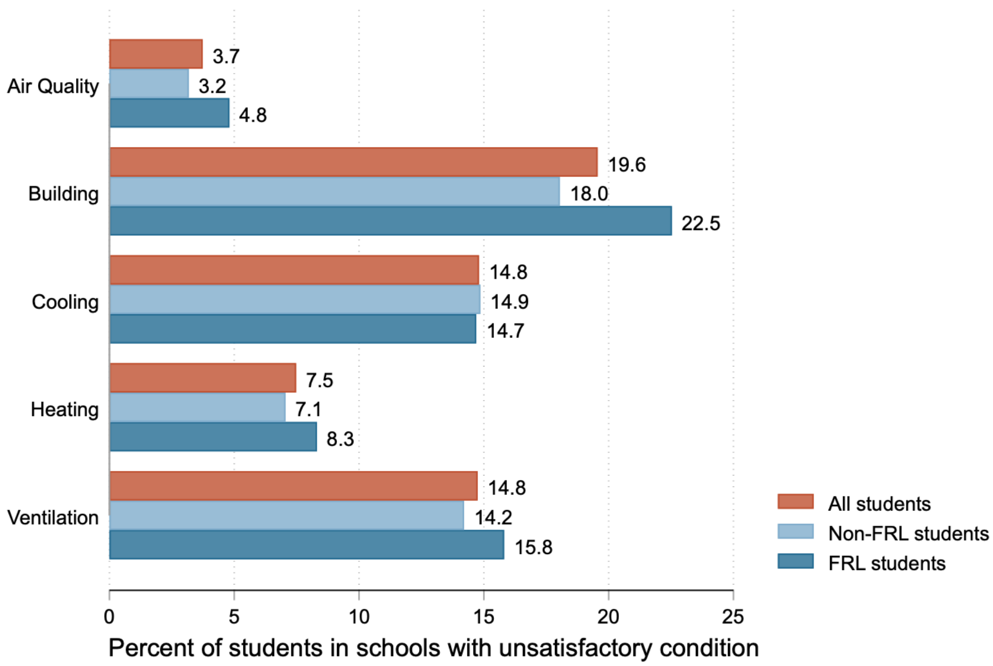
Tables and Figures

Figure 1. Exposure to Unsatisfactory HVAC Conditions by Student Characteristics

(a) By Student Economic Status



(b) By Student Race/Ethnicity

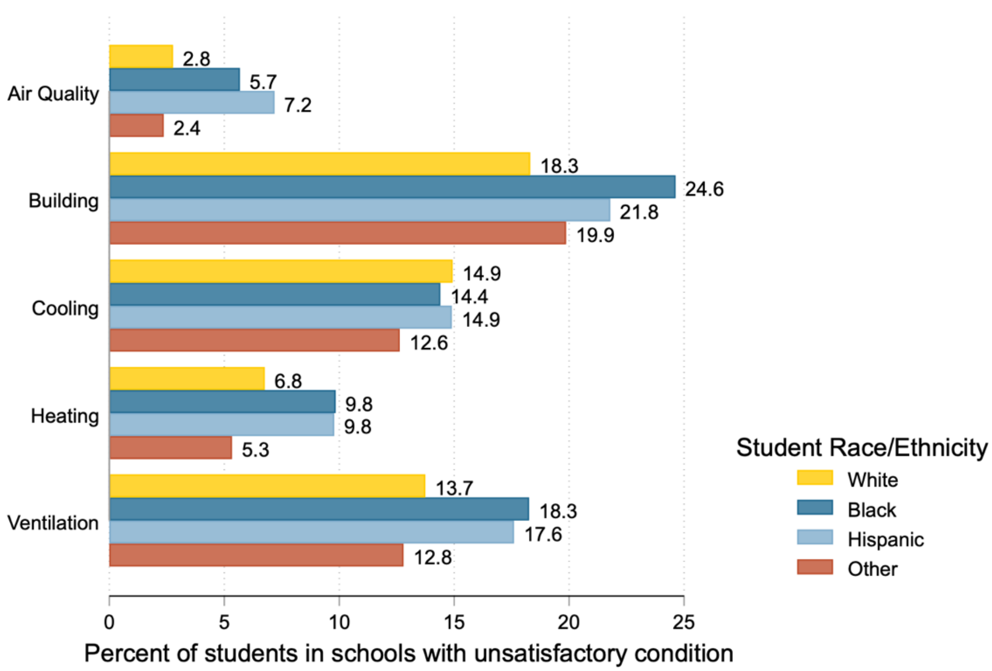
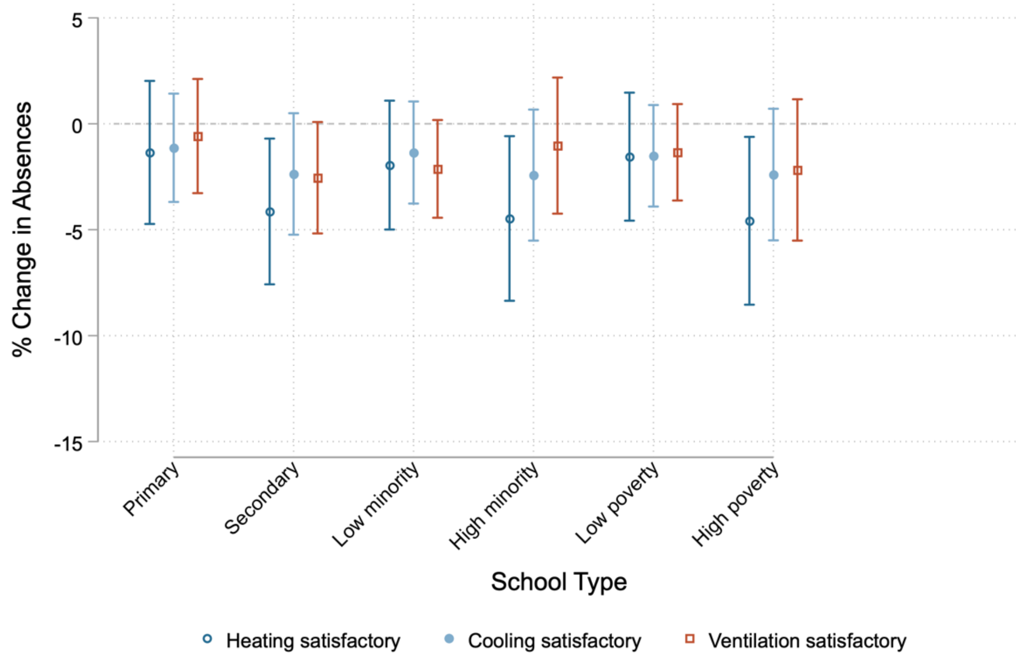
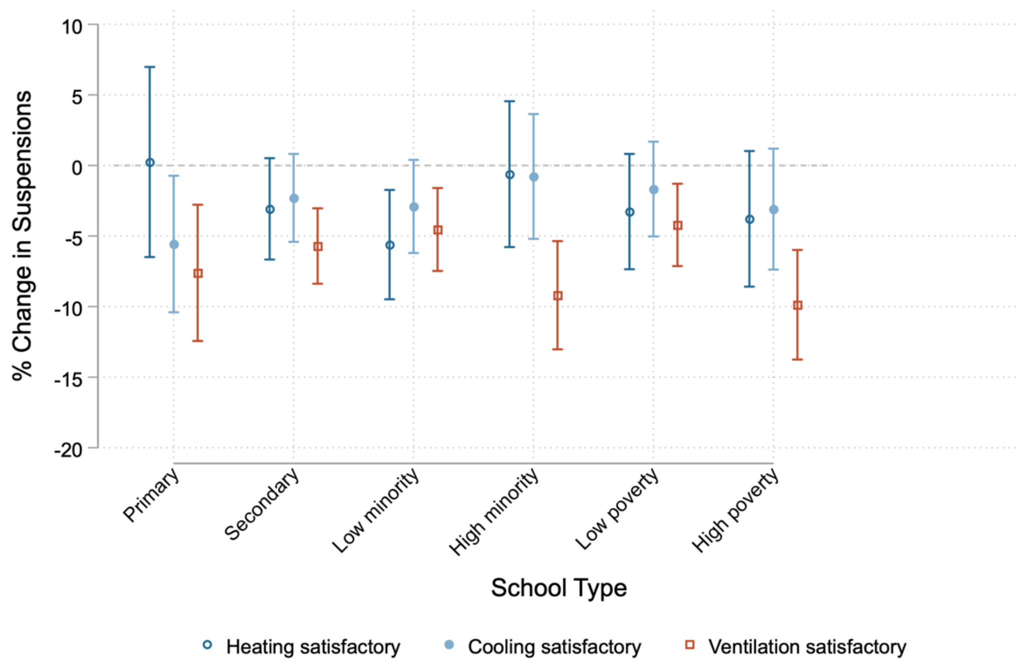


Figure 2. Effect of Satisfactory System Condition on Student Outcomes by School Type

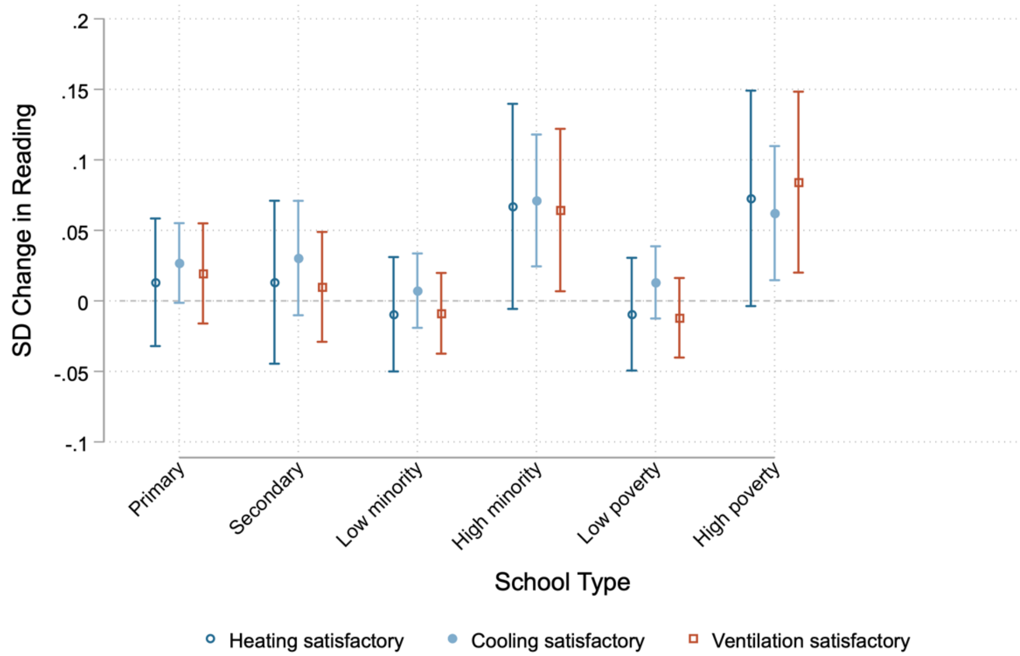
(a) Absence Rate



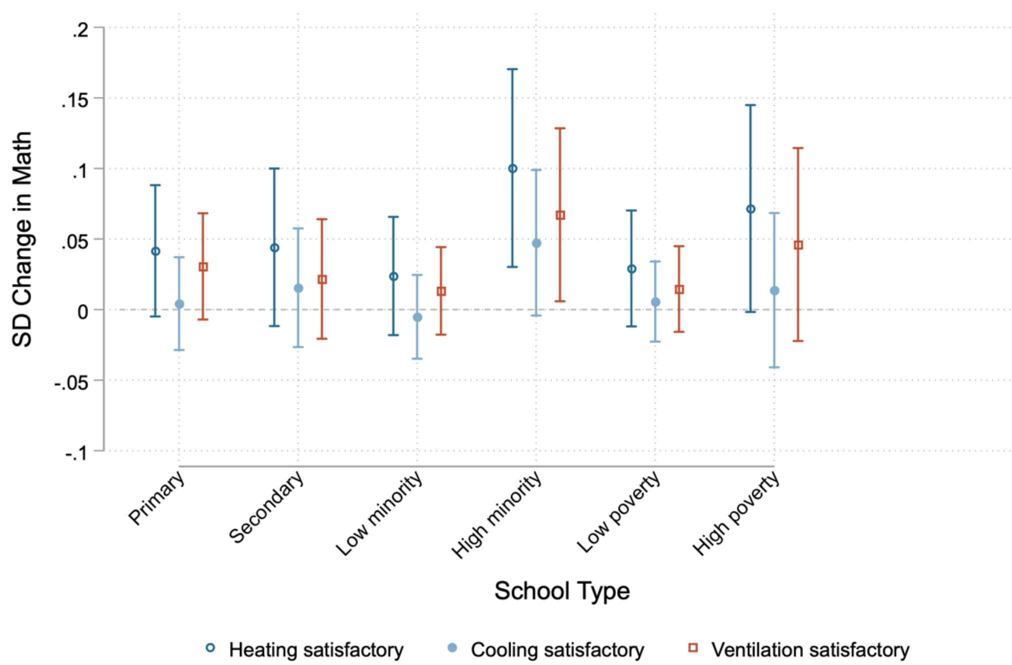
(b) Suspension Rate



(c) ELA Scores



(d) Math Scores

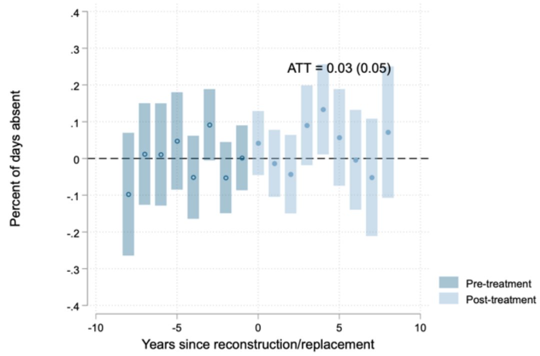


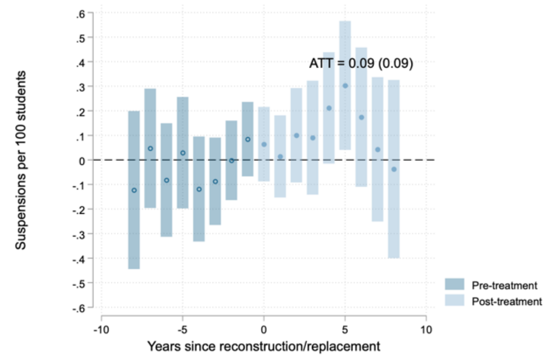
Note. These represent estimates on satisfactory HVAC system condition from separate regressions with school and year fixed effects and covariates. High minority schools have less than 70% White enrollment; high-poverty schools have more than 50% FRPL enrollment. 95% confidence intervals shown.

Figure 3. Event Studies of HVAC Reconstruction/Replacement and Behavioral Outcomes

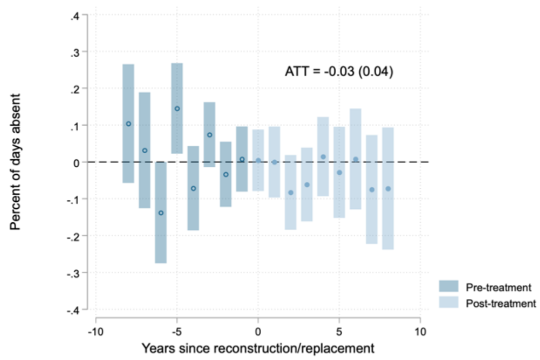
System	Absence Rate	Suspension Rate

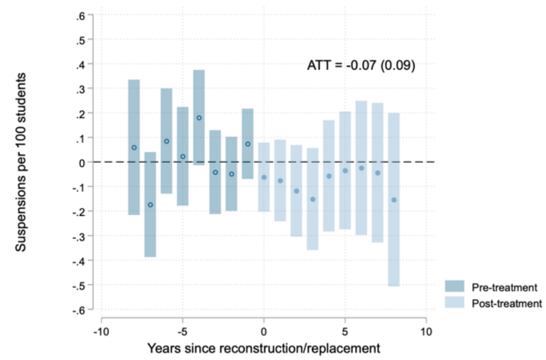
Cooling



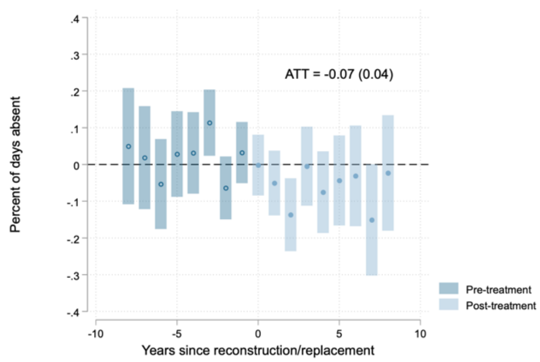


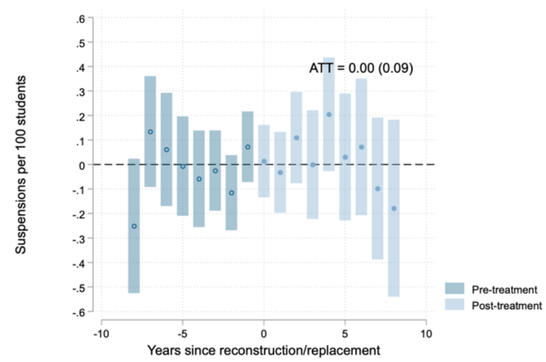
Heating





Ventilation



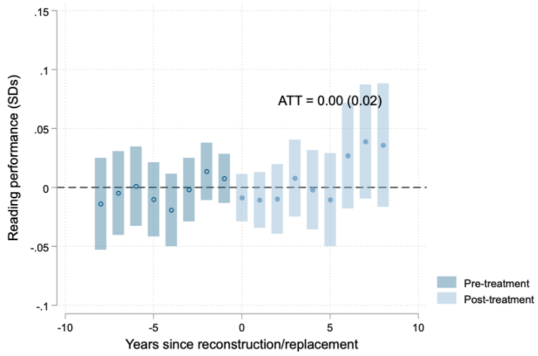


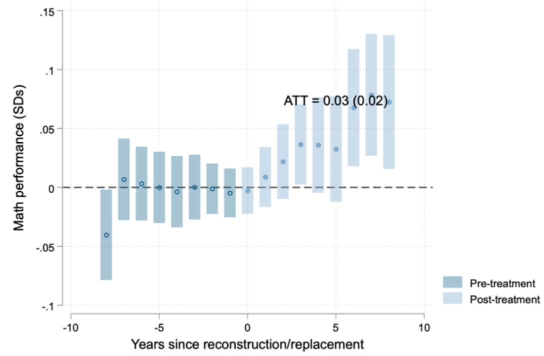
Note. All event studies above come from the Callaway and Sant'Anna (2021) doubly robust difference-in-differences estimator, with stabilized inverse probability weighting based on baseline covariates of pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American, and percent students multiracial. The event window is restricted to 8 years prior and 8 years following an HVAC system reconstruction or replacement. 95% confidence intervals shown in shaded region.

Figure 4. Event Studies of HVAC Reconstruction/Replacement and Achievement Outcomes

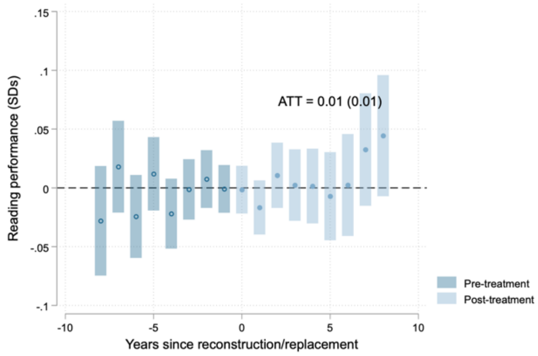
System	ELA Scores	Math Scores

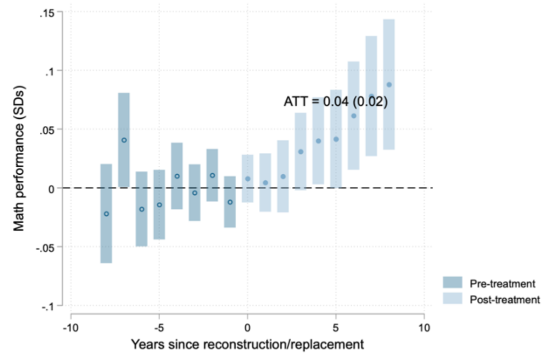
Cooling



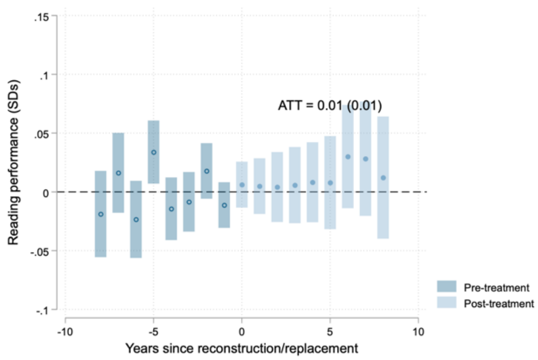


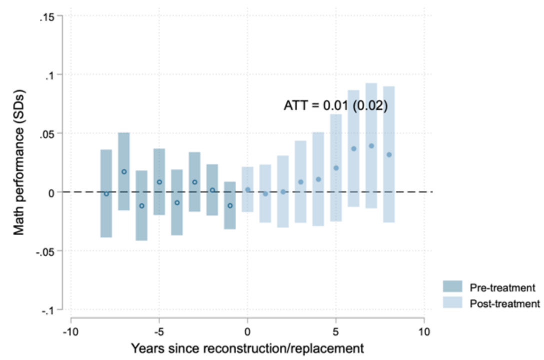
Heating





Ventilation





Note. All event studies above come from the Callaway and Sant'Anna (2021) doubly robust difference-in-differences estimator, with stabilized inverse probability weighting based on baseline covariates of pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American, and percent students multiracial. The event window is restricted to 8 years prior and 8 years following an HVAC system reconstruction or replacement. 95% confidence intervals shown in shaded region.

Table 1. Descriptive Statistics of School-Level Data 2006-2019

Variable	(1) Mean / Prop.	(2) SD
Outcomes		
Percent of days absent	5.107	2.281
Suspensions per 100 students	3.201	4.154
Reading performance (SDs)	0.041	0.924
Math performance (SDs)	0.042	0.914
Building and environmental conditions		
Cooling system condition satisfactory	0.845	NA
Heating system condition satisfactory	0.930	NA
Ventilation system condition satisfactory	0.859	NA
Indoor air quality satisfactory	0.846	NA
Overall building condition satisfactory	0.744	NA
Years remaining cooling system	14.45	9.173
Years remaining heating system	17.21	11.28
Years remaining ventilation system	12.28	10.47
Building construction year	1954	19.49
Major renovation past year	0.480	NA
Days below 0 degrees Celsius	33.36	18.42
Days above 30 degrees Celsius	8.298	5.447
Average PM2.5 pollution	8.198	1.870
School characteristics		
Elementary school	0.559	NA
Middle school	0.177	NA
High school	0.207	NA
Other grade configuration	0.053	NA
City locale	0.088	NA
Suburb locale	0.476	NA
Town locale	0.121	NA
Rural locale	0.243	NA
Student enrollment	574.4	375.5
Pupil-to-teacher ratio	13.37	4.077
Construction outlay per pupil ($)	13,512	50,307
Percent students free/reduced price lunch	36.41	24.74
Percent students White	71.62	28.52
Percent students Black	10.08	16.90
Percent students Hispanic	11.96	16.09
Percent students Asian	3.940	6.154
Percent students multiracial	1.694	3.146

Note. For student-weighted descriptive statistics see Appendix Table A3.

Table 2. Effects of HVAC System Condition Changes on Student Outcomes

	(1) Absence (Per 100)	(2) Suspension (Per 100)	(3) Reading (SDs)	(4) Math (SDs)
Cooling system satisfactory	-0.0176+	-0.0233+	0.0285*	0.0075
	(0.010)	(0.014)	(0.012)	(0.013)
Heating system satisfactory	-0.0293*	-0.0370*	0.0159	0.0462*
	(0.013)	(0.016)	(0.018)	(0.018)
Ventilation satisfactory	-0.0169+	-0.0643**	0.0157	0.0282+
	(0.010)	(0.013)	(0.014)	(0.015)
Estimator	Poisson	Poisson	OLS	OLS
Controls	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	32,899	28,924	28,609	28,609
Schools	2,751	2,443	2,310	2,308

+p<0.1, *p<0.05, **p<0.01

Note. Robust standard errors in parentheses, clustered by school. All models include school and year fixed effects and control variables: pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American, and percent students multiracial.

Table 3. Effects of HVAC System Reconstructions/Replacements on Student Outcomes

	(1) Absence (Per 100)	(2) Suspension (Per 100)	(3) Reading (SDs)	(4) Math (SDs)
Cooling system replacement	0.0259	0.0853	0.0050	0.0341*
	(0.045)	(0.094)	(0.015)	(0.016)
	N=35,254	N=32,666	N=30,447	N=30,443
Heating system replacement	-0.0305	-0.0731	0.0096	0.0391*
	(0.043)	(0.092)	(0.014)	(0.016)
	N=35,283	N=32,679	N=30,454	N=30,449
Ventilation replacement	-0.0717+	0.0047	0.0077	0.0132
	(0.041)	(0.092)	(0.015)	(0.016)
	N=35,198	N=32,656	N=30,399	N=30,395
Estimator	CSDID	CSDID	CSDID	CSDID
Controls	Yes	Yes	Yes	Yes

+p<0.1, *p<0.05, **p<0.01

Note. Robust standard errors in parentheses, clustered by school. All models estimated using the Callaway and Sant'Anna (2021) doubly robust difference-in-differences estimator with stabilized inverse probability weighting and ordinary least squares. Inverse probability weighting based on earliest period covariates of: pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American, and percent students multiracial.

Appendix

Figure A1. Histogram of Building Condition Survey Years

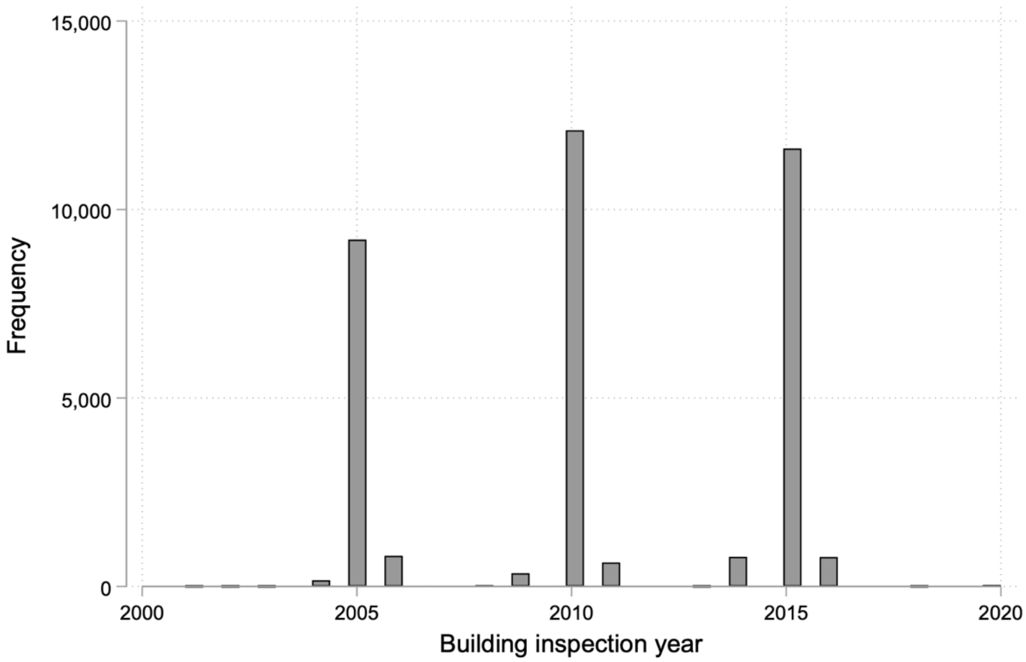


Figure A2. Histogram of School Building Construction Year

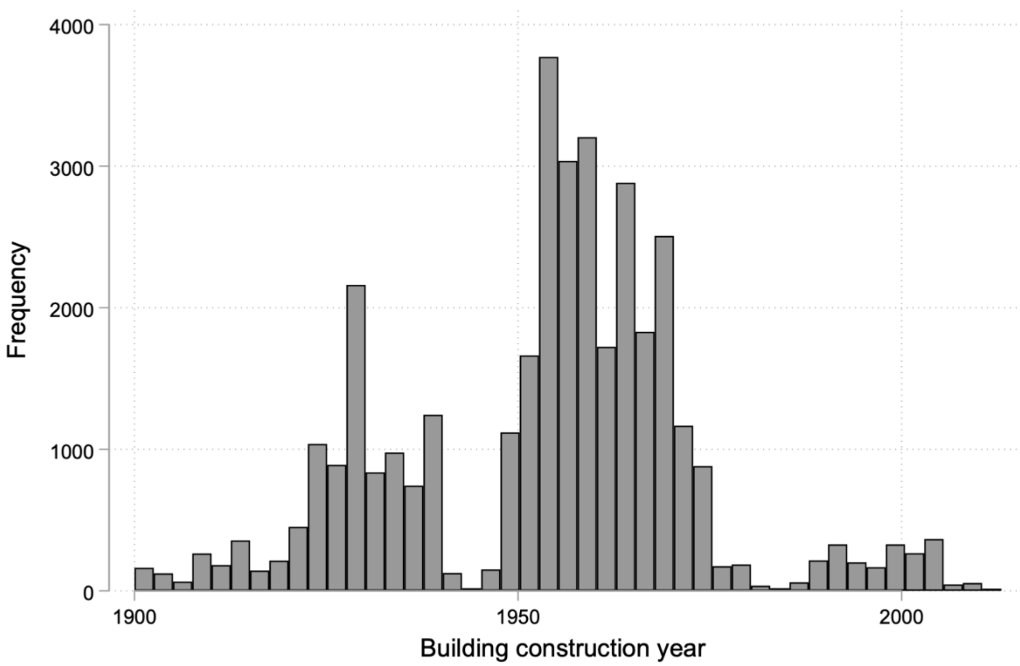
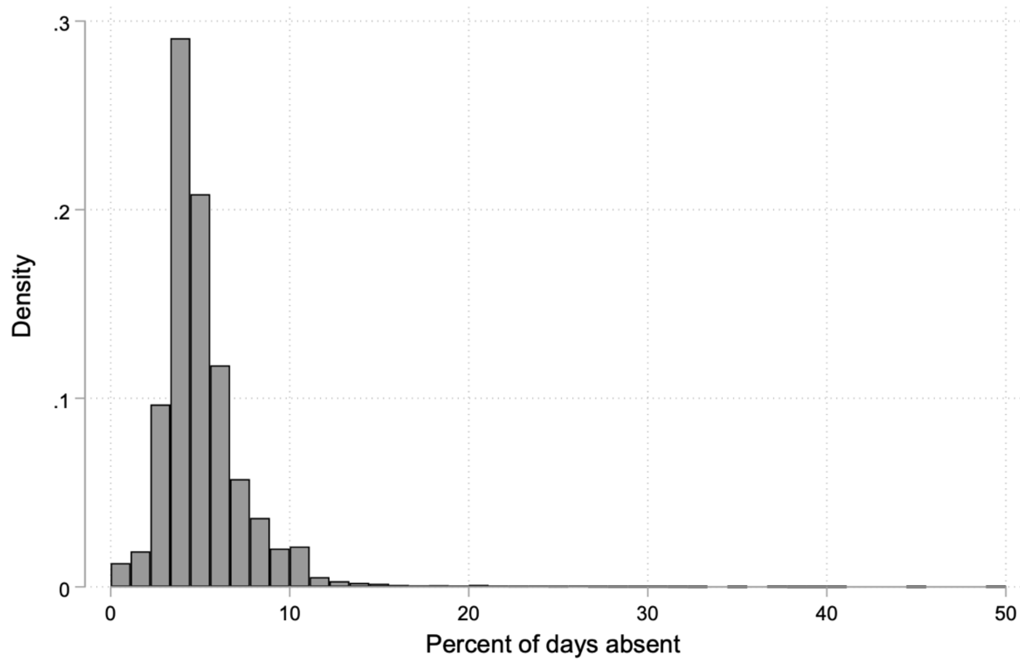


Figure A3. Histograms of Count Outcome Measures

(a) Student Absences



(b) Student Suspensions

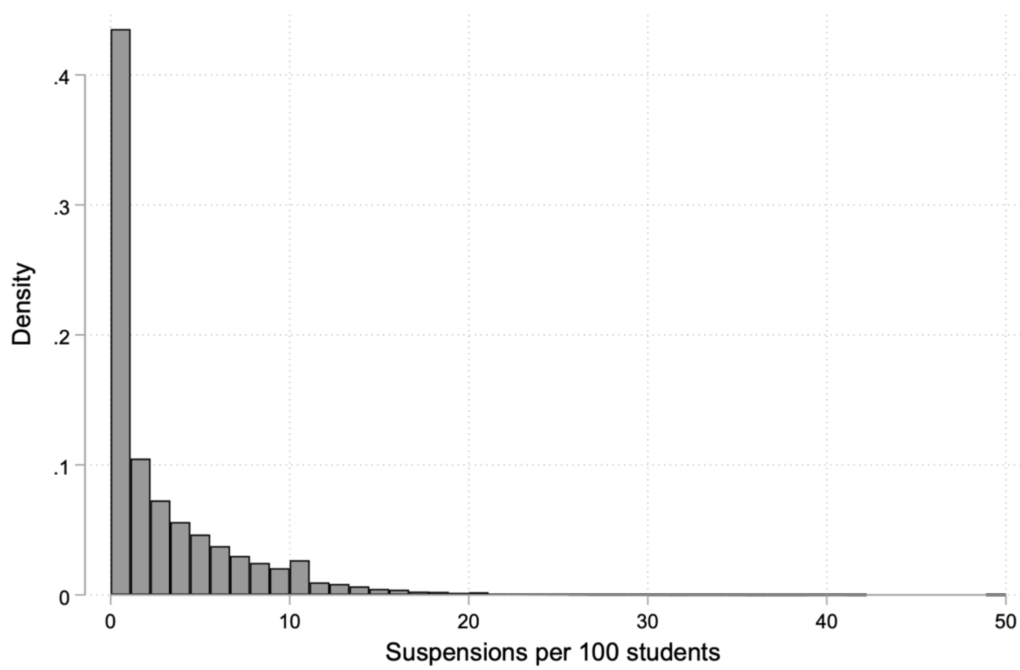


Figure A4. NY Schools with Unsatisfactory Cooling Systems in 2019, by Number of Hot Days

Note. Schools marked in dark red had 15 or more days, schools in medium red had 6-15 days, and schools in light red had 6 or fewer days with temperature over 30 degrees Celsius in the 2018-2019 school year.

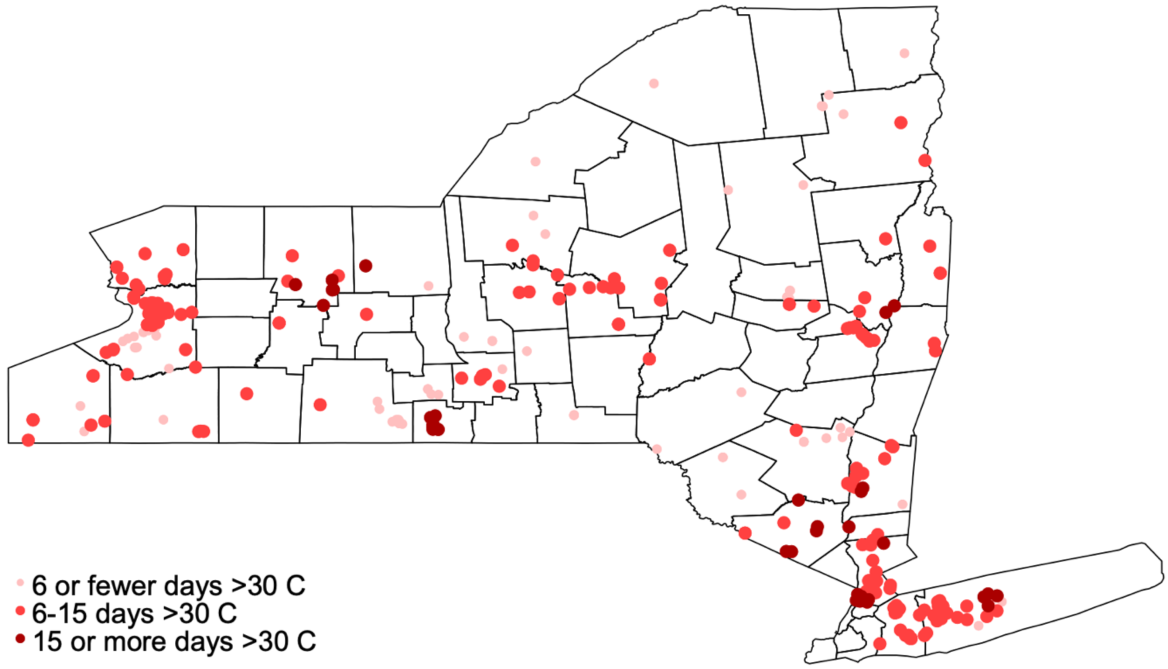
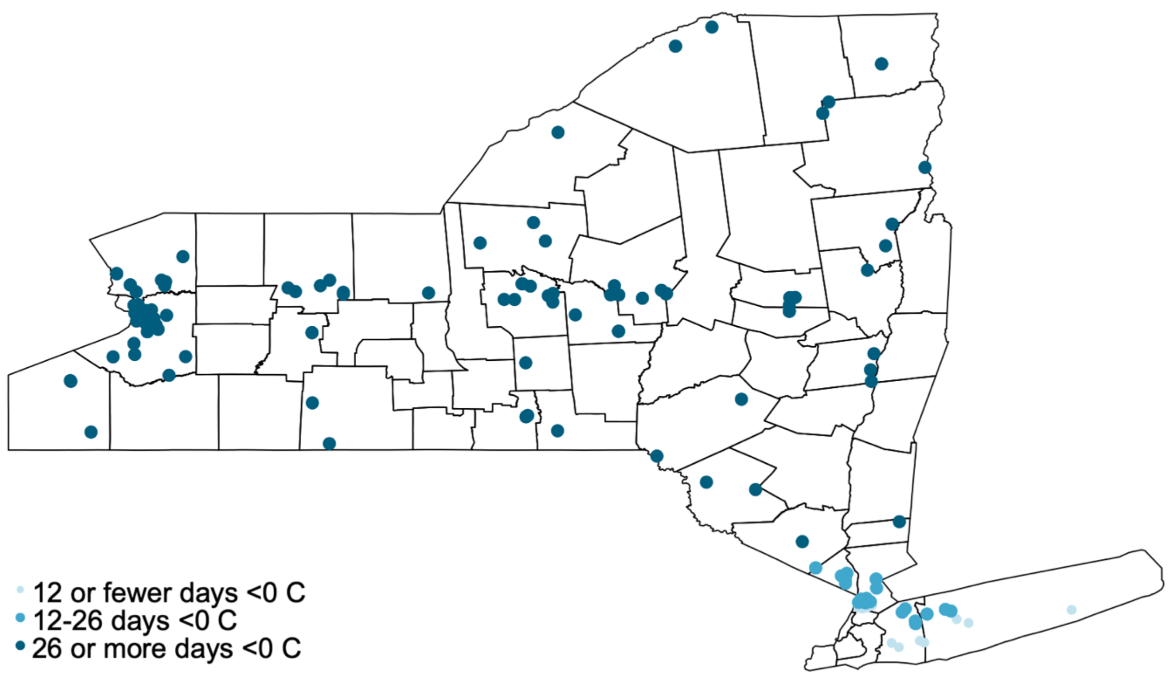


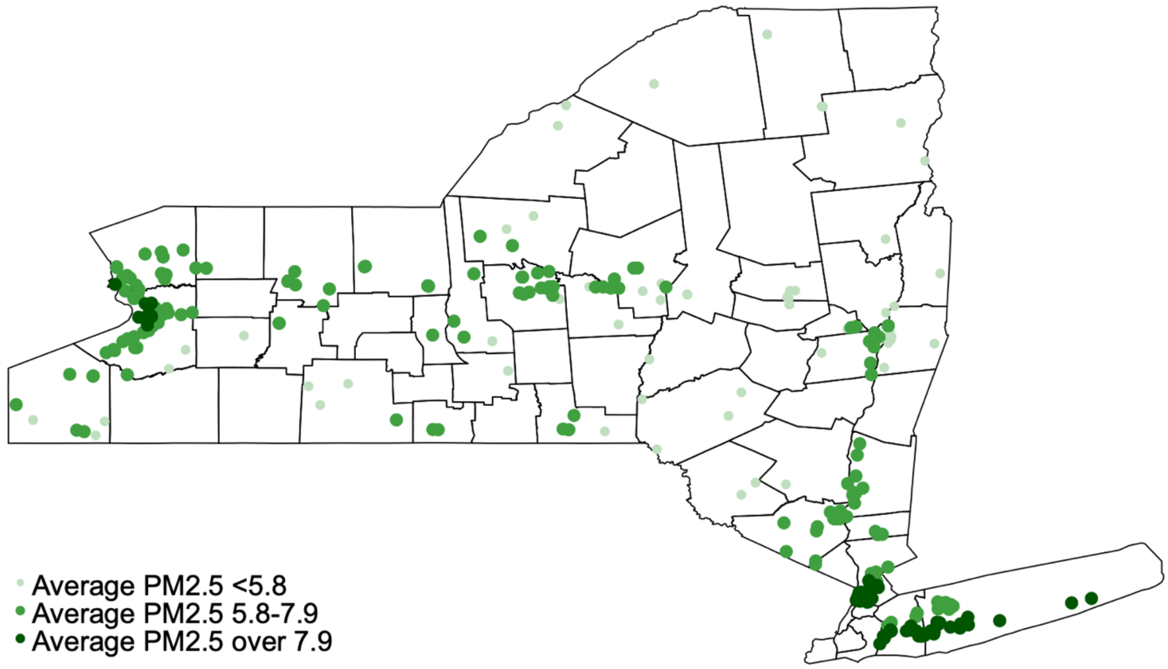
Figure A5. NY Schools with Unsatisfactory Heating Systems in 2019, by Number of Cold Days

Note. Schools marked in dark blue h



ad 26 or more days, schools marked in medium blue had 12 to 26 days, and schools marked in light blue had 12 or fewer days with temperature below 0 degrees Celsius in the 2018-2019 school year.

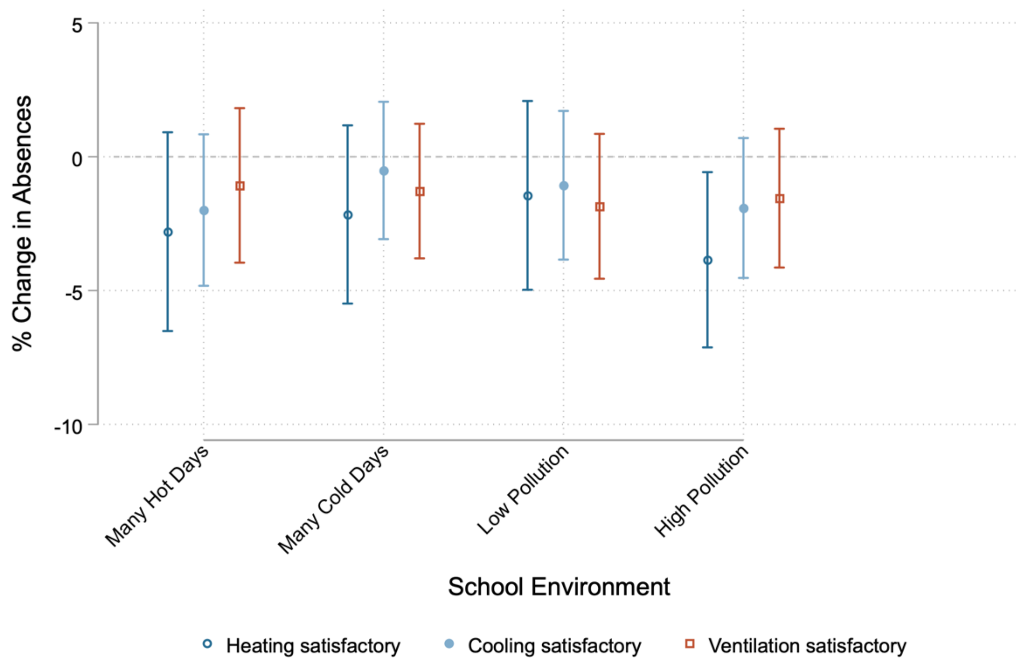
Figure A6. NY Schools with Unsatisfactory Ventilation Systems in 2019, by Air Pollution Levels



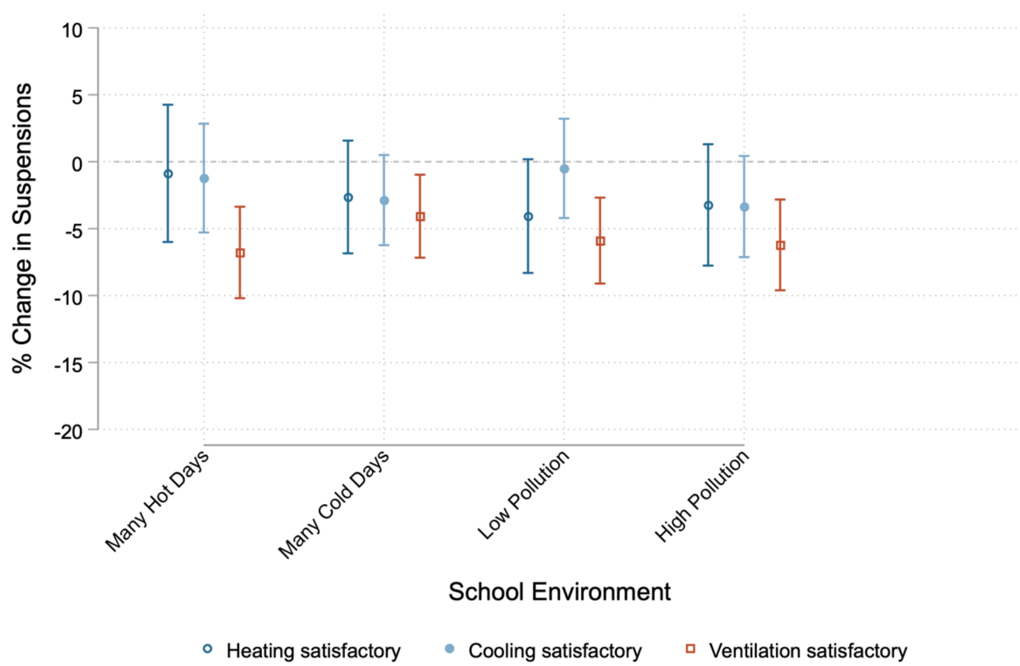
Note. Schools marked in dark green had average PM2.5 levels of over 7.9, schools marked in medium green had average PM2.5 levels of between 5.8 and 7.9, and schools marked in light green had less than 5.8 average PM2.5 levels in the 2015-2016 school year.

Figure A7. Effect of Satisfactory HVAC System Condition on Outcomes by School Environment

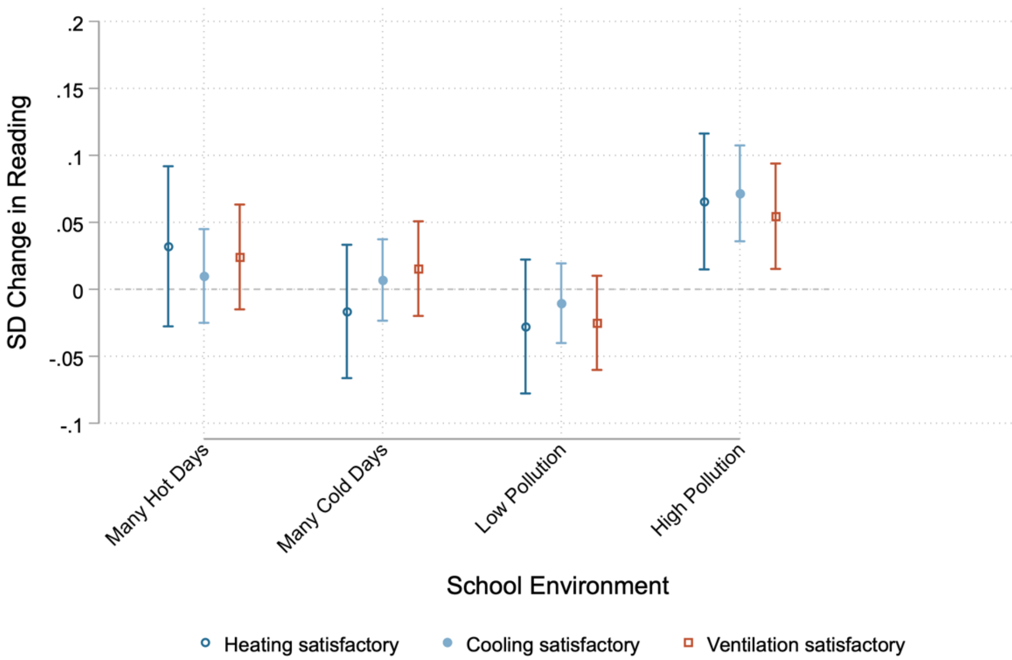
(a) Absence Rate



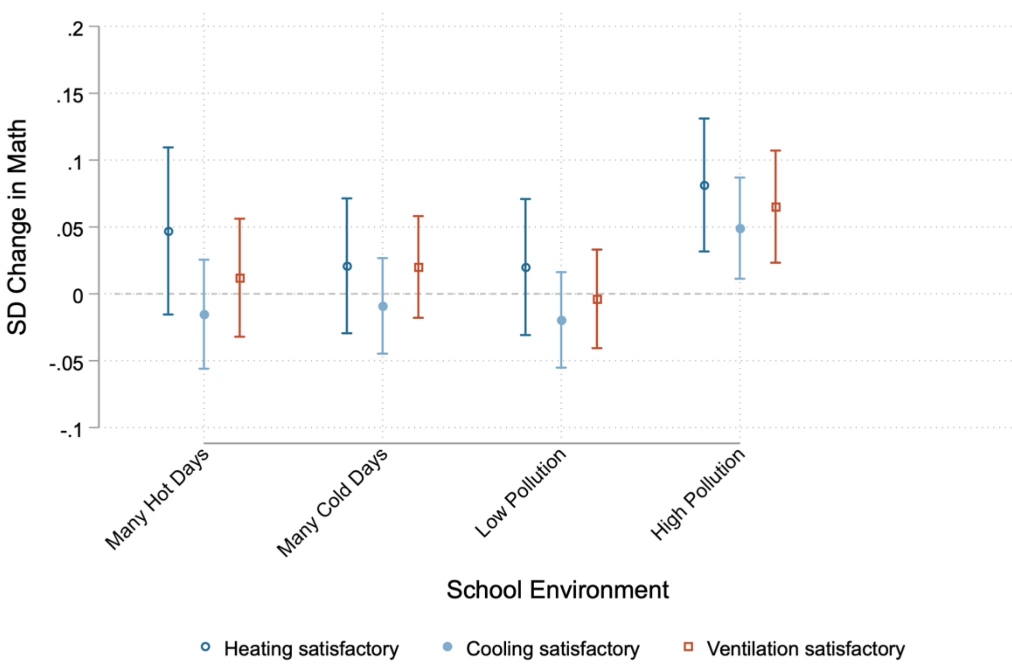
(b) Suspension Rate



(c) Reading Scores



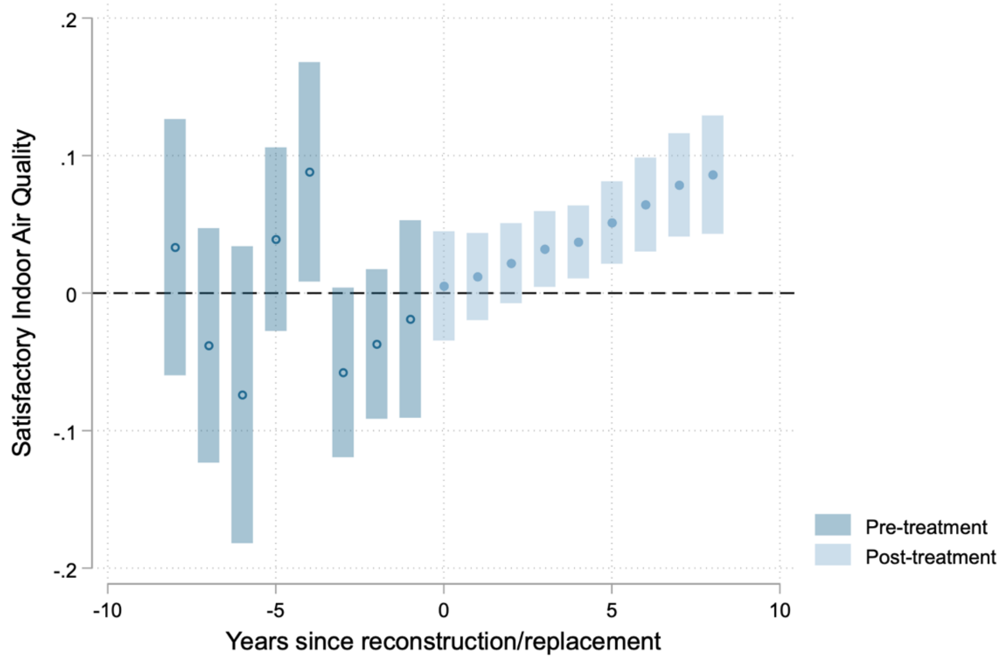
(d) Math Scores



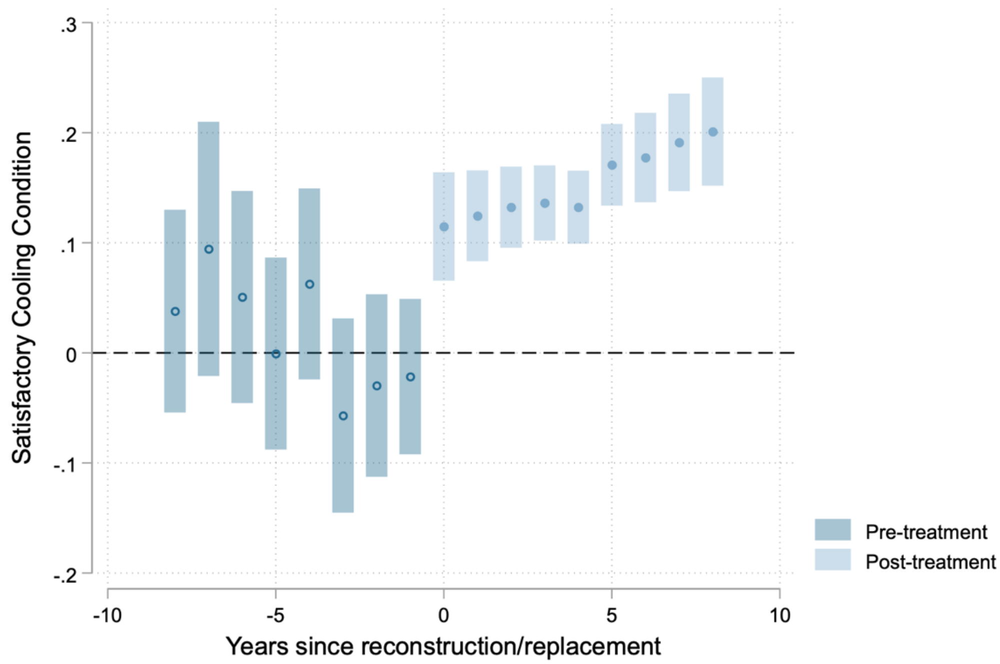
Note. Each panel shows the estimated effect of satisfactory HVAC system condition for schools in different environments. Regions are defined by whether schools are above or below the median in annual days above 30°C (hot), days below 0°C (cold), or average PM2.5 levels (polluted). Specifications follow Table 2. 95% confidence intervals shown.

Figure A8. Effects of HVAC System Reconstruction/Replacement on Building Conditions

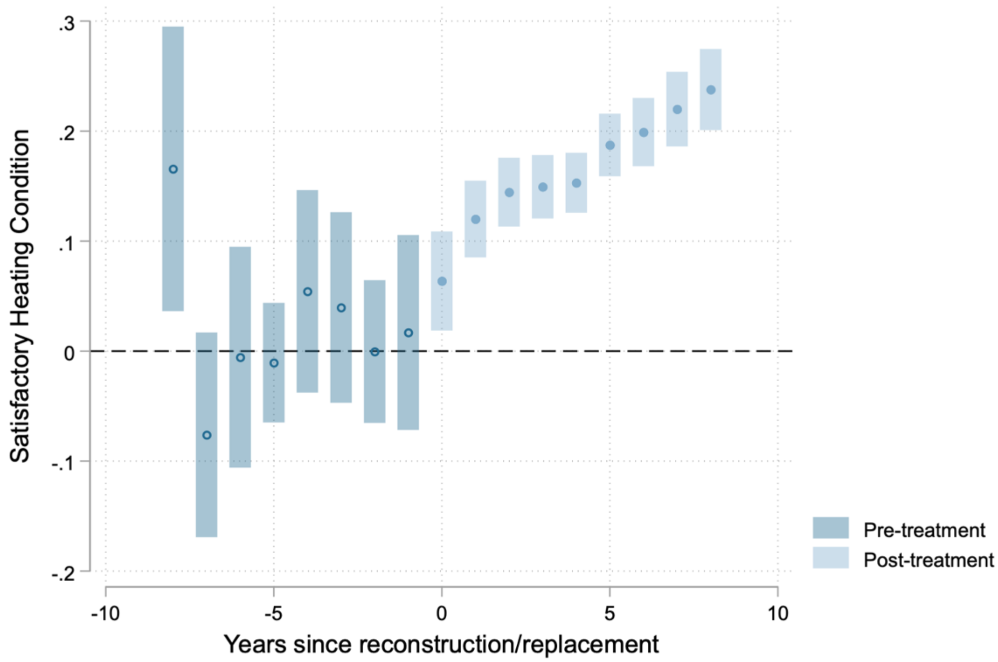
(a) Effects of Any HVAC System Event on Satisfactory Indoor Air Quality



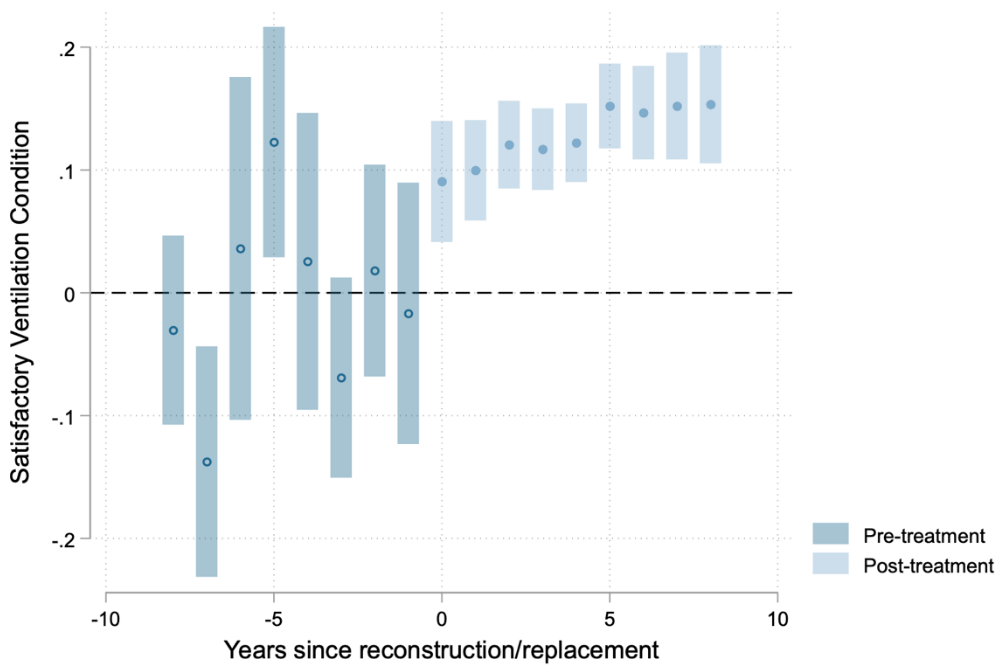
(b) Effects of Cooling System Event on Satisfactory Cooling System Condition



(c) Effects of Heating System Event on Satisfactory Heating System Condition



(d) Effects of Ventilation System Event on Satisfactory Ventilation System Condition



Note. These event studies come from the Callaway and Sant'Anna (2021) difference-in-differences estimator, with stabilized inverse probability weighting based on pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, and percent of students by race/ethnicity. The event window is restricted to 8 years prior and 8 years following an HVAC system reconstruction or replacement. 95% confidence intervals shown in shaded region.

Table A1. Definitions of System Condition Ratings

Rating	Definition
Excellent	System is in new or like-new condition and functioning optimally. No remediation required. Requires only routine maintenance as identified in the building comprehensive maintenance plan.
Satisfactory	System functioning reliably; routine maintenance and repair required.
Unsatisfactory	System is functioning unreliably or has exceeded its useful life. A corrective action plan is in place and repairs or replacement of some or all components has been scheduled.
Non-Functioning	System is non-functioning, not functioning as designed, or is unreliable in ways that could endanger occupant health and/or safety. Repair or replacement of some or all components is needed.
Critical Failure	System is non-functioning, not functioning as designed, or is unreliable in ways that could endanger occupant health and/or safety. The condition of at least one component is so poor that at least part of the building or grounds should not be occupied pending repair or replacement of some or all components.

Table A2. Full Tabulation of School HVAC System Condition Ratings

Condition	(1) Cooling	(2) Heating	(3) Ventilation
Excellent	5.8%	11.2%	4.7%
Satisfactory	78.7%	81.9%	81.2%
Unsatisfactory	4.6%	6.2%	12.2%
Non-functional	10.9%	0.7%	1.9%

Note. Satisfactory and excellent are aggregated into a single "satisfactory" category, and unsatisfactory and non-functional are aggregated into a single "not satisfactory" category.

Table A3. Student-Weighted Descriptive Statistics

Variable	(1) Weighted Mean	(2) SE
Outcomes		
Percent of days absent	5.266	0.055
Suspensions per 100 students	3.803	0.097
Reading performance (SDs)	0.071	0.020
Math performance (SDs)	0.069	0.020
Building and environmental conditions		
Cooling system condition satisfactory	0.852	0.005
Heating system condition satisfactory	0.925	0.004
Ventilation system condition satisfactory	0.852	0.005
Indoor air quality satisfactory	0.841	0.005
Overall building condition satisfactory	0.747	0.007
Years remaining cooling system	14.18	0.142
Years remaining heating system	17.11	0.168
Years remaining ventilation system	11.97	0.164
Building construction year	1955	0.406
Major renovation past year	0.507	0.008
Days below 0 degrees Celsius	31.30	0.305
Days above 30 degrees Celsius	8.450	0.070
Average PM2.5 pollution	8.453	0.029
School characteristics		
Elementary school	0.444	0.011
Middle school	0.196	0.009
High school	0.318	0.012
Other grade configuration	0.039	0.003
City locale	0.093	0.006
Suburb locale	0.547	0.009
Town locale	0.101	0.005
Rural locale	0.182	0.007
Student enrollment	819.8	19.72
Pupil-to-teacher ratio	13.67	0.045
Construction outlay per pupil ($)	11,170	487.8
Percent students free/reduced price lunch	34.41	0.518
Percent students White	69.13	0.645
Percent students Black	10.92	0.365
Percent students Hispanic	13.48	0.404
Percent students Asian	4.445	0.142
Percent students multiracial	1.484	0.030

Note. Student-weighted descriptive statistics weight each school-year observation by student enrollment using survey estimation (svyset). Survey mean and standard error of the mean are shown for each variable. Sample consists of N=39,506 school-year observations.

Table A4. Number of Schools with Major Changes in HVAC System Condition

System	(1) Any Change in Condition	(2) Improvement Only	(3) Deterioration Only	(4) Improvement and Deterioration
Cooling system	1,241	559	380	302
	(43.5%)	(19.6%)	(13.3%)	(10.6%)
Heating system	955	384	329	242
	(33.5%)	(13.5%)	(11.5%)	(8.5%)
Ventilation system	1,249	509	428	312
	(43.7%)	(17.8%)	(15.0%)	(10.9%)

Note. Each cell shows the number of schools with the specified type of change in system condition between 2006 and 2019. The number in parentheses is the percent of total schools in our sample (2,855) with the specified type of change in system.

Table A5. Effects of HVAC System Condition on Indoor Air Quality

	(1) Air Quality Fair/Good	(2) Air Quality Poor	(3) Air Quality Fair	(4) Air Quality Good
Cooling system satisfactory	0.0679**	-0.0241*	-0.0402+	0.1081**
	(0.013)	(0.010)	(0.021)	(0.021)
Heating system satisfactory	0.1032**	-0.0444**	-0.0405	0.1437**
	(0.018)	(0.013)	(0.026)	(0.025)
Ventilation satisfactory	0.1208**	-0.0850**	-0.0631**	0.1839**
	(0.014)	(0.011)	(0.021)	(0.019)
Estimator	OLS	OLS	OLS	OLS
Controls	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	36,474	36,474	36,474	36,474
Schools	2,834	2,834	2,834	2,834

Note. Each outcome is a binary indicator based on a Likert rating question about indoor air quality from the Building Condition Survey. Robust standard errors in parentheses, clustered by school. All models include school and year fixed effects and control variables: pupil-to-teacher ratio, log enrollment, percent students free or reduced price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American and percent students multiracial.

Table A6. Effects of Satisfactory Cooling System Conditions on Student Outcomes by School Characteristics

School Type	(1) Absence (Per 100)	(2) Suspension (Per 100)	(3) Reading (SDs)	(4) Math (SDs)
Primary	-0.0114	-0.0573*	0.0269+	0.0043
	(0.013)	(0.026)	(0.014)	(0.017)
	n= 18,475	n= 15,904	n= 18,602	n= 18,602
Secondary	-0.0240	-0.0232	0.0304	0.0155
	(0.015)	(0.016)	(0.021)	(0.021)
	n= 14,336	n= 12,920	n= 9,985	n= 9,985
Low minority	-0.0137	-0.0295+	0.0072[a]	-0.0051
	(0.012)	(0.017)	(0.013)	(0.015)
	n= 23,115	n= 21,209	n= 19,830	n= 19,829
High minority	-0.0245	-0.0078	0.0712**[a]	0.0474+
	(0.016)	(0.023)	(0.024)	(0.026)
	n= 9,784	n= 7,715	n= 8,779	n= 8,780
Low poverty	-0.0152	-0.0169	0.0131	0.0057
	(0.012)	(0.017)	(0.013)	(0.014)
	n= 24,254	n= 21,783	n= 20,193	n= 20,190
High poverty	-0.0243	-0.0314	0.0622*	0.0138
	(0.016)	(0.023)	(0.024)	(0.028)
	n= 8,645	n= 7,141	n= 8,416	n= 8,419
Estimator	Poisson	Poisson	OLS	OLS
Controls	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

+p<0.1, *p<0.05, **p<0.01; a: significantly different than counterpart group at p<0.05.
Note. SD = standard deviation. Each cell represents the main coefficient estimate from a separate regression. Robust standard errors in parentheses, clustered by school. All models include school and year fixed effects and control variables: pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American, and percent students multiracial.

Table A7. Effects of Satisfactory Heating System Conditions on Student Outcomes by School Characteristics

School Type	(1) Absence (Per 100)	(2) Suspension (Per 100)	(3) Reading (SDs)	(4) Math (SDs)
Primary	-0.0136	0.0025[a]	0.0132	0.0416+
	(0.017)	(0.034)	(0.023)	(0.024)
	n= 18,475	n= 15,904	n= 18,602	n= 18,602
Secondary	-0.0423*	-0.0312+[a]	0.0132	0.0441
	(0.018)	(0.019)	(0.029)	(0.028)
	n= 14,336	n= 12,920	n= 9,985	n= 9,985
Low minority	-0.0197	-0.0577**	-0.0095	0.0238
	(0.016)	(0.021)	(0.021)	(0.021)
	n= 23,115	n= 21,209	n= 19,830	n= 19,829
High minority	-0.0457*	-0.0062	0.0670+	0.1003**
	(0.021)	(0.027)	(0.037)	(0.036)
	n= 9,784	n= 7,715	n= 8,779	n= 8,780
Low poverty	-0.0156	-0.0332	-0.0095	0.0292
	(0.016)	(0.022)	(0.020)	(0.021)
	n= 24,254	n= 21,783	n= 20,193	n= 20,190
High poverty	-0.0469*	-0.0386	0.0727+	0.0716+
	(0.021)	(0.025)	(0.039)	(0.037)
	n= 8,645	n= 7,141	n= 8,416	n= 8,419
Estimator	Poisson	Poisson	OLS	OLS
Controls	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

+p<0.1, *p<0.05, **p<0.01; a: significantly different than counterpart group at p<0.1.

Note. SD = standard deviation. Each cell represents the main coefficient estimate from a separate regression. Robust standard errors in parentheses, clustered by school. All models include school and year fixed effects and control variables: pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American, and percent students multiracial.

Table A8. Effects of Satisfactory Ventilation System Conditions on Student Outcomes by School Characteristics

School Type	(1) Absence (Per 100)	(2) Suspension (Per 100)	(3) Reading (SDs)	(4) Math (SDs)
Primary	-0.0058	-0.0792**	0.0194	0.0306
	(0.014)	(0.027)	(0.018)	(0.019)
	n= 18,475	n= 15,904	n= 18,602	n= 18,602
Secondary	-0.0258+	-0.0588**	0.0099	0.0217
	(0.014)	(0.014)	(0.020)	(0.022)
	n= 14,336	n= 12,920	n= 9,985	n= 9,985
Low minority	-0.0215+	-0.0464**[a]	-0.0088[a]	0.0132
	(0.012)	(0.016)	(0.015)	(0.016)
	n= 23,115	n= 21,209	n= 19,830	n= 19,829
High minority	-0.0104	-0.0965**[a]	0.0644*[a]	0.0672*
	(0.017)	(0.022)	(0.029)	(0.031)
	n= 9,784	n= 7,715	n= 8,779	n= 8,780
Low poverty	-0.0135	-0.0431**	-0.0120[a]	0.0146
	(0.012)	(0.016)	(0.014)	(0.015)
	n= 24,254	n= 21,783	n= 20,193	n= 20,190
High poverty	-0.0220	-0.1039**	0.0842*[a]	0.0461
	(0.017)	(0.022)	(0.033)	(0.035)
	n= 8,645	n= 7,141	n= 8,416	n= 8,419
Estimator	Poisson	Poisson	OLS	OLS
Controls	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

+p<0.1, *p<0.05, **p<0.01; a: significantly different than counterpart group at p<0.1.
Note. SD = standard deviation. Each cell represents the main coefficient estimate from a separate regression. Robust standard errors in parentheses, clustered by school. All models include school and year fixed effects and control variables: pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American, and percent students multiracial.

Table A9. Effects of HVAC System Reconstructions/Replacements on Student Outcomes by Baseline HVAC and Environmental Conditions

Reconstruction/ Replacement	(1) Absence (Per 100)	(2) Suspension (Per 100)	(3) Reading (SDs)	(4) Math (SDs)
Cooling				
Hot region	0.0487	0.0907	-0.0007	0.0172
	(0.071)	(0.137)	(0.020)	(0.022)
Cold region	0.0341	0.0059	-0.0132	0.0127
	(0.055)	(0.137)	(0.019)	(0.021)
Low pollution	0.0312	0.1376	-0.0223	0.0052
	(0.054)	(0.115)	(0.019)	(0.020)
High pollution	0.0170	0.0004	0.0400	0.0559*
	(0.080)	(0.167)	(0.025)	(0.026)
System	0.4733	-0.5692	0.0439	0.2324
unsatisfactory	(0.416)	(0.728)	(0.199)	(0.155)
Building	-0.0511	0.5850	-0.0932	-0.0442
unsatisfactory	(0.161)	(0.383)	(0.068)	(0.046)
Heating				
Hot region	-0.0082	-0.0209	-0.0154	0.0098
	(0.065)	(0.132)	(0.019)	(0.022)
Cold region	-0.0305	-0.0319	0.0175	0.0372+
	(0.056)	(0.141)	(0.019)	(0.020)
Low pollution	-0.0131	-0.0376	0.0028	0.0146
	(0.054)	(0.119)	(0.019)	(0.020)
High pollution	-0.0405	-0.0721	0.0255	0.0652**
	(0.071)	(0.150)	(0.023)	(0.024)
System	0.1396	-0.0930	-0.6277	-0.0077
unsatisfactory	(0.366)	(3.203)	(0.421)	(0.333)
Building	-1.3439	1.1875*	-0.9302	0.8072
unsatisfactory	(0.998)	(0.570)	(0.970)	(0.547)
Ventilation				
Hot region	-0.0880	0.0823	-0.0021	-0.0039
	(0.061)	(0.133)	(0.020)	(0.023)
Cold region	-0.0581	-0.0447	0.0153	0.0086
	(0.052)	(0.134)	(0.019)	(0.021)
Low pollution	-0.0806	0.0170	0.0003	-0.0082
	(0.049)	(0.114)	(0.018)	(0.020)
High pollution	-0.0389	-0.0410	0.0063	0.0135
	(0.076)	(0.166)	(0.025)	(0.028)
System	-0.4056	-0.2380	-0.0755	0.0100
unsatisfactory	(0.282)	(0.653)	(0.099)	(0.091)
Building	-0.2897+	0.8888*	-0.0505	-0.1464

Reconstruction/ Replacement	(1) Absence (Per 100)	(2) Suspension (Per 100)	(3) Reading (SDs)	(4) Math (SDs)
unsatisfactory	(0.175)	(0.366)	(0.099)	(0.101)
Estimator	CSDID	CSDID	CSDID	CSDID
Controls	Yes	Yes	Yes	Yes

+p<0.1, *p<0.05, **p<0.01

Note. Regions are defined by whether schools are above or below the median in annual days above 30°C (hot), days below 0°C (cold), or average PM2.5 levels (polluted). Robust standard errors in parentheses, clustered by school. All models estimated using the Callaway and Sant'Anna (2021) doubly robust difference-in-differences estimator with stabilized inverse probability weighting and ordinary least squares. Inverse probability weighting based on earliest period covariates of: pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American, and percent students multiracial.

Table A10. Effects of HVAC System Condition Changes on School Covariates

	(1) Percent FRL	(2) Percent Nonwhite	(3) Pupil-Teacher Ratio	(4) Log Enrollment
Cooling system satisfactory	0.0015 (0.002)	0.0035+ (0.002)	-0.0129 (0.095)	0.0055 (0.005)
Heating system satisfactory	-0.0040 (0.003)	0.0026 (0.002)	-0.1102 (0.092)	0.0025 (0.007)
Ventilation satisfactory	0.0019 (0.002)	0.0001 (0.002)	0.0288 (0.053)	0.0097+ (0.005)
Estimator	OLS	OLS	OLS	OLS
Controls	No	No	No	No
School FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	36,560	36,560	36,560	36,560
Schools	2,834	2,834	2,834	2,834

+p<0.1, *p<0.05, **p<0.01

Note. Each cell represents the main coefficient estimate from a separate regression. Robust standard errors in parentheses, clustered by school. All models include school and year fixed effects.

Table A11. Effects of HVAC System Condition on Student Outcomes, All Same Regression

	(1) Absence (Per 100)	(2) Suspension (Per 100)	(3) Reading (SDs)	(4) Math (SDs)
Cooling system satisfactory	-0.0130	0.0056	0.0232+	-0.0024
	(0.011)	(0.015)	(0.012)	(0.014)
Heating system satisfactory	-0.0216	0.0033	0.0196	0.0469*
	(0.014)	(0.019)	(0.019)	(0.020)
Ventilation satisfactory	-0.0068	-0.0677**	-0.0004	0.0158
	(0.011)	(0.015)	(0.015)	(0.016)
Estimator	Poisson	Poisson	OLS	OLS
Controls	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	29,937	26,091	26,231	26,231
Schools	2,751	2,421	2,305	2,303

Note. Robust standard errors in parentheses, clustered by school. All models include school and year fixed effects and control variables: pupil-to-teacher ratio, log enrollment, percent students free or reduced price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American and percent students multiracial. All three HVAC system conditions are included in the same regression in this specification.

Table A12. Effects of Any or All HVAC Systems in Satisfactory Condition on Student Outcomes

	(1) Absence (Per 100)	(2) Suspension (Per 100)	(3) Reading (SDs)	(4) Math (SDs)
Any system satisfactory	-0.0447*	-0.1052**	0.0630*	0.0698*
	(0.020)	(0.026)	(0.031)	(0.031)
All systems satisfactory	-0.0069	-0.0278**	0.0182*	0.0201*
	(0.007)	(0.009)	(0.009)	(0.010)
Estimator	Poisson	Poisson	OLS	OLS
Controls	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	32,899	28,924	28,609	28,609
Schools	2,751	2,443	2,310	2,308

+p<0.1, *p<0.05, **p<0.01

Note. SD = standard deviation. Each cell represents the coefficient estimate from a separate regression. Robust standard errors in parentheses, clustered by school. All models include school fixed effects, year fixed effects, and control variables: pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American, and percent students multiracial.

Table A13. Effects of Detailed HVAC System Condition on Student Outcomes

	(1) Absence (Per 100)	(2) Suspension (Per 100)	(3) Reading (SDs)	(4) Math (SDs)
Cooling system unsatisfactory	Omitted	Omitted	Omitted	Omitted
Cooling system satisfactory	-0.0179+	-0.0235+	0.0280*	0.0069
	(0.010)	(0.014)	(0.012)	(0.014)
Cooling system excellent	-0.0143	-0.0222	0.0341	0.0138
	(0.016)	(0.021)	(0.021)	(0.024)
Heating system unsatisfactory	Omitted	Omitted	Omitted	Omitted
Heating system satisfactory	-0.0283*	-0.0380*	0.0155	0.0446*
	(0.013)	(0.017)	(0.019)	(0.019)
Heating system excellent	-0.0353*	-0.0305	0.0185	0.0552*
	(0.015)	(0.020)	(0.021)	(0.022)
Ventilation unsatisfactory	Omitted	Omitted	Omitted	Omitted
Ventilation satisfactory	-0.0161+	-0.0634**	0.0141	0.0269+
	(0.010)	(0.013)	(0.014)	(0.015)
Ventilation excellent	-0.0272	-0.0770**	0.0349	0.0447+
	(0.018)	(0.024)	(0.022)	(0.025)
Estimator	Poisson	Poisson	OLS	OLS
Controls	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	32,899	28,924	28,609	28,609
Schools	2,751	2,443	2,310	2,308

+p<0.1, *p<0.05, **p<0.01

Note. Robust standard errors in parentheses, clustered by school. All models include school and year fixed effects and control variables: pupil-to-teacher ratio, log enrollment, percent students free or reduced price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American and percent students multiracial.

Table A14. Effects of HVAC System Condition Improvements and Deteriorations on Student Outcomes

	(1) Absence (Per 100)	(2) Suspension (Per 100)	(3) Reading (SDs)	(4) Math (SDs)
Cooling system improvement	-0.0219*	0.0093	0.0520**	0.0335+
	(0.009)	(0.028)	(0.016)	(0.018)
Heating system improvement	-0.0280*	-0.0170	0.0341	0.0707**
	(0.012)	(0.033)	(0.022)	(0.023)
Ventilation improvement	-0.0171+	-0.0709**	0.0205	0.0194
	(0.009)	(0.027)	(0.017)	(0.019)
Cooling system deterioration	0.0152	0.0881*	0.0282	0.0416+
	(0.011)	(0.040)	(0.022)	(0.025)
Heating system deterioration	0.0239*	0.0640	-0.0009	-0.0200
	(0.012)	(0.044)	(0.030)	(0.031)
Ventilation deterioration	0.0154	0.0693*	-0.0049	-0.0387
	(0.010)	(0.031)	(0.022)	(0.024)
Estimator	Poisson	Poisson	OLS	OLS
Controls	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	32,899	28,924	28,609	28,609
Schools	2,751	2,678	2,310	2,308

+p<0.1, *p<0.05, **p<0.01

Note. SD = standard deviation. Each cell represents the main coefficient estimate from a separate regression. Robust standard errors in parentheses, clustered by school. All models include school fixed effects, year fixed effects, and control variables: pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American, and percent students multiracial.

Table A15. Effects of HVAC System Reconstructions/Replacements: Robustness Tests

	(1) Absence (Per 100)	(2) Suspension (Per 100)	(3) Reading (SDs)	(4) Math (SDs)
(a) Never treated as a comparison group				
Cooling system replacement	0.0306	0.0419	0.0080	0.0374*
	(0.045)	(0.094)	(0.015)	(0.016)
	N=35,253	N=32,666	N=30,446	N=30,442
Heating system replacement	-0.0269	-0.0711	0.0085	0.0408**
	(0.043)	(0.092)	(0.014)	(0.016)
	N=35,283	N=32,679	N=30,454	N=30,449
Ventilation replacement	-0.0683+	-0.0153	0.0110	0.0174
	(0.041)	(0.093)	(0.015)	(0.017)
	N=35,198	N=32,656	N=30,398	N=30,394
(b) HVAC events in major renovation years excluded				
Cooling system replacement	-0.0021	0.0532	-0.0004	0.0229
	(0.051)	(0.108)	(0.016)	(0.018)
	N=35,263	N=32,682	N=30,511	N=30,507
Heating system replacement	-0.0446	-0.0561	0.0018	0.0383*
	(0.047)	(0.102)	(0.015)	(0.017)
	N=35,273	N=32,679	N=30,495	N=30,490
Ventilation replacement	-0.0964*	-0.0395	-0.0055	0.0096
	(0.047)	(0.105)	(0.016)	(0.018)
	N=35,207	N=32,667	N=30,455	N=30,451
Estimator	CSDID	CSDID	CSDID	CSDID
Controls	Yes	Yes	Yes	Yes

+p<0.1, *p<0.05, **p<0.01

Note. Robust standard errors in parentheses, clustered by school. All models estimated using the Callaway and Sant'Anna (2021) doubly robust difference-in-differences estimator with stabilized inverse probability weighting and ordinary least squares. Inverse probability weighting based on earliest period covariates of: pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students Black, percent students Hispanic, percent students Asian, percent students Native American, and percent students multiracial.

Table A16. Effects of Satisfactory HVAC System Conditions on Student Outcomes: Robustness Tests

System Satisfactory	(1) No controls	(2) Renov. controls	(3) Survey year	(4) Balanced panel	(5) Student-weighted	(6) Dist-year FE	(7) DiDM
				Absence (Per 100)			
Cooling	-0.0185+	-0.0175+	-0.0201	-0.0218*	-0.0190+	-0.0188**	-0.1291+
	(0.010)	(0.010)	(0.017)	(0.011)	(0.010)	(0.005)	(0.069)
	N=32,965	N=29,937	N=12,405	N=27,981	N=32,899	N=31,538	N=16,206
Heating	-0.0295*	-0.0268*	-0.0432*	-0.0273*	-0.0368**	-0.0089	-0.1906
	(0.013)	(0.013)	(0.022)	(0.013)	(0.014)	(0.006)	(0.202)
	N=32,965	N=29,937	N=12,405	N=27,981	N=32,899	N=31,538	N=16,394
Ventilation	-0.0177+	-0.0159	-0.0123	-0.0204+	-0.0158+	-0.0055	-0.0163
	(0.010)	(0.010)	(0.017)	(0.010)	(0.009)	(0.005)	(0.098)
	N=32,965	N=29,937	N=12,405	N=27,981	N=32,899	N=31,538	N=16,239
				Suspensions (Per 100)			
Cooling	-0.0257+	-0.0160	0.0006	-0.0373*	-0.0452+	-0.0106	-0.1358
	(0.014)	(0.015)	(0.023)	(0.015)	(0.026)	(0.020)	(0.103)
	N=28,957	N=26,091	N=10,059	N=24,973	N=28,924	N=27,224	N=14,476
Heating	-0.0413*	-0.0246	-0.0473+	-0.0462**	-0.0481	-0.0171	-0.4378
	(0.016)	(0.017)	(0.028)	(0.017)	(0.031)	(0.021)	(0.315)
	N=28,957	N=26,091	N=10,059	N=24,973	N=28,924	N=27,224	N=15,057
Ventilation	-0.0736**	-0.0653**	-0.0661**	-0.0777**	-0.0666**	-0.0585**	-0.2752
	(0.013)	(0.013)	(0.022)	(0.014)	(0.023)	(0.018)	(0.173)
	N=28,957	N=26,091	N=10,059	N=24,973	N=28,924	N=27,224	N=14,489
				Reading (SDs)			
Cooling	0.0254*	0.0250*	0.0121	0.0233+	0.0416**	0.0340*	0.0307
	(0.012)	(0.012)	(0.016)	(0.013)	(0.013)	(0.016)	(0.019)
	N=28,609	N=26,231	N=10,186	N=24,165	N=28,589	N=26,892	N=14,227
Heating	0.0141	0.0233	0.0182	0.0257	0.0268	0.0359+	0.0341
	(0.019)	(0.018)	(0.024)	(0.020)	(0.018)	(0.021)	(0.045)
	N=28,609	N=26,231	N=10,186	N=24,165	N=28,589	N=26,892	N=15,003
Ventilation	0.0143	0.0105	0.0104	0.0178	0.0191	0.0244	-0.0088
	(0.014)	(0.013)	(0.018)	(0.015)	(0.013)	(0.018)	(0.023)
	N=28,609	N=26,231	N=10,186	N=24,165	N=28,589	N=26,892	N=14,295
				Math (SDs)			

System Satisfactory	(1) No controls	(2) Renov. controls	(3) Survey year	(4) Balanced panel	(5) Student-weighted	(6) Dist-year FE	(7) DiDM
Cooling	0.0003	0.0064	0.0062	0.0093	0.0066	0.0336+	-0.0101
	(0.014)	(0.014)	(0.018)	(0.014)	(0.014)	(0.018)	(0.021)
	N=28,609	N=26,231	N=10,184	N=24,163	N=28,593	N=26,895	N=14,225
Heating	0.0419*	0.0530**	0.0511*	0.0572**	0.0465*	0.0500*	0.1104*
	(0.019)	(0.019)	(0.025)	(0.019)	(0.019)	(0.023)	(0.048)
	N=28,609	N=26,231	N=10,184	N=24,163	N=28,593	N=26,895	N=15,002
Ventilation	0.0251+	0.0265+	0.0099	0.0390*	0.0224	0.0344+	0.0646**
	(0.015)	(0.014)	(0.019)	(0.016)	(0.016)	(0.020)	(0.024)
	N=28,609	N=26,231	N=10,184	N=24,163	N=28,593	N=26,895	N=14,296

+p<0.1, *p<0.05, **p<0.01.

Note. Each cell shows coefficient, SE in parentheses, and observations. All specifications include school and year fixed effects. No controls: No covariates included. Renov. controls: Major renovation indicator and capital outlay expenditures controlled for in addition to main covariates. Survey year: sample restricted to only Building Condition Survey years (2005, 2010, 2015). Balanced panel: sample restricted to only schools with full year coverage of all variables. Student-weighted: all specifications use student enrollment as frequency weights. Dist-year FE: model includes district-by-year fixed effects (OLS for absence and suspensions). DiDM: de Chaisemartin & D'Haultfoeuille (2026) estimator with four years of post-treatment dynamic effects estimated.