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

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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 outside New York City 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 absence, reduce student suspension, and modestly increase student math and reading scores. Heating and cooling system replacements and reconstructions also increase student math achievement. We conclude that investments made now to improve school HVAC systems can benefit not only student comfort and well-being, but also enhance educational opportunity.

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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 outside New York City 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 absence, reduce student suspension, and modestly increase student math and reading scores. Heating and cooling system replacements and reconstructions also increase student math achievement. We conclude that investments made now to improve school HVAC systems can benefit not only student comfort and well-being, but also enhance educational opportunity.

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During the Delta wave of the COVID-19 pandemic in summer of 2021, Secretary of Education Miguel Cardona identified ventilation system improvement as the number one investment school districts should prioritize for safe school reopening (Lombardo, 2021). Even prior to the pandemic, the U.S. Government Accountability Office identified an estimated 36,000 school buildings nationwide as having inadequate heating, ventilation, and air (HVAC) systems (Nowicki, 2020). Further, school districts serving high proportions of low-income students struggle disproportionately with HVAC system inadequacies (Alexander and Lewis., 2014). It comes as no surprise, therefore, that many school districts have decided to spend some portion of their received federal COVID relief funds on facility improvements, generally, and on HVAC system repair specifically (Silberstein & Roza, 2023). South Dakota, for example, spent over half of their American Rescue Plan funding on school facility improvements (Belsha, 2024).

Some have critiqued this choice to spend federal funds on building facilities instead of instructional time as potentially misguided (Brooks & Springer, 2024), given the enormous academic learning loss experienced by many students following the pandemic (Lewis & Kuhfeld, 2023). Growing evidence, however, points to the possibility that these two goals – improving school building conditions and supporting student learning recovery – may not represent a tradeoff. Some recent literature shows that school capital investments can benefit student learning over the long term (Biasi et al., 2024; Hong & Zimmer, 2016; Lafortune & Schönholzer, 2022). Furthermore, studies have demonstrated that air quality in schools in particular can causally affect student learning (Gilraine, 2020; Persico & Venator, 2021), as can air temperature in schools (Carlson & Shepardson, 2024; Park et al., 2020). Theoretically, air quality could affect student attendance or learning through its contribution to student health problems such as asthma or allergies. Ventilation quality could affect the spread of contagious disease within classrooms. And variation in classroom temperature, such as extreme heat or cold, could affect students' abilities to concentrate.

This study contributes to our understanding of how school environmental conditions shape student academic and behavioral outcomes using a new dataset of all public school buildings from the 2005-06 to 2018-19 school years in New York State outside of New York City. Specifically, we ask within this sample: (i) How does access to well-functioning HVAC systems vary by student socioeconomic status and race/ethnicity? (ii) What are the effects of changes in school HVAC system conditions on student absenteeism, suspension, and reading and math test scores? And (iii) What are the effects of school HVAC system reconstructions and replacements on student absenteeism, suspension, and reading and math test scores?

To address these questions, we first scrape detailed information on building conditions, HVAC system conditions, and HVAC system reconstructions/repairs from public building inspection report documents and link these measures to educational variables from the New York State Education Department (NYSED). We observe that economically disadvantaged students, Black students, and Hispanic students all have greater exposure to unsatisfactory building conditions, air quality, heating systems, and ventilation systems. We also observe that many schools with non-functional heating systems reside in areas of the state regularly experiencing below-freezing temperatures, many schools with non-functional cooling systems reside in areas regularly experiencing extremely hot temperatures, and many schools with non-functional ventilation systems reside in areas with high average particulate pollution in the air. To the extent that such systems affect student health or learning, inadequate HVAC system conditions in school buildings could exacerbate health, social, and educational inequalities.

Using traditional difference-in-difference methods and those that account for issues associated with staggered treatment timing (Callaway & Sant'Anna, 2021; De Chaisemartin & d'Haultfoeuille, 2024), we proceed to estimate the effects of HVAC system condition changes on student outcomes. We find that schools with satisfactory heating system conditions reduce student absence by 3%, reduce student suspensions by 6%, and improve student math scores by 5% of a standard deviation, compared to schools with unsatisfactory or non-functional heating systems. Schools with satisfactory ventilation system conditions also reduce student absence by 2% and student suspension by 7% compared to those with unsatisfactory or non-functional ventilation systems. Finally, satisfactory cooling system conditions increase student reading scores by 3% of a standard deviation but have no effect on other outcomes. When looking at HVAC system reconstructions and replacements, there are fewer immediate effects, but there are significant improvements in math performance in the magnitude of 3% of a standard deviation for cooling system reconstructions or replacements and 4% of a standard deviation for heating system reconstructions or replacements. In sum, our study provides new evidence supporting the broad value of school facility improvements for promoting student well-being and educational equity.

Building Environmental Conditions, Health, and Learning

Outside of just schools, a vast public health literature documents the importance of office and home building conditions and ventilation for human health. Several studies have focused on the positive effects on health or reduction of transmission of airborne particles when better ventilation is available in building premises. Occupants of poorly-ventilated buildings with high occupant densities have a greater probability of respiratory illness than occupants of better-ventilated buildings (Seppänen et al., 1999). Recent innovations in HVAC technology have shown significant enhancements to indoor air quality, subsequently leading to healthier and more sustainable indoor environments. Furthermore, investments in advanced HVAC systems offer substantial economic advantages through improved health outcomes and increased productivity (Tashtoush et al, 2005; Petrov, 2024).

Because of this connection to disease transmission, building ventilation has also been linked previously to absenteeism due to sickness. Milton et al. (2000) reported an apparent 35% reduction in sick leave rates associated with increased ventilation and absence of humidification. His results revealed that 57% of all sick leave (5 annual sick leave days) was due to lower ventilation among exposed workers. A previous study (Teculescu et al., 1998) also showed that occupants of an air-conditioned building were more likely to exhibit absence from work than employees in a naturally ventilated building. Correspondingly, research indicates that occupants of air-conditioned offices have more sick building syndrome symptoms than occupants of naturally ventilated offices (Seppänen and Fisk, 2002; Arif et al.,2016).

The relation between building conditions and health also translates to the context of schools. Mendell et al. (2013) calculated that increasing the ventilation rates of the classrooms to the state standard would decrease illness absence rates by 3.4%. Observations from a study from Shendell et al. (2004) incorporating 409 normal classrooms and 25 portable classrooms in Washington and Idaho revealed 0.5%–0.9% average lower attendance in classrooms where indoor CO_2 was regularly surpassing 1000 ppm and 2% lower attendance in portable classrooms than the typical one. A study linking 2005 school absenteeism with 2005 school building conditions in Upstate New York revealed that schools with 6 or more adverse exposures to mold, moisture, ventilation, or vermin also had increased odds of higher absenteeism (Simons et al., 2010). A systematic review by Fisk (2017) presented evidence that reduced respiratory health effects and reduced student absences are positively associated with increased ventilation facilities. Out of the 11 studies he reviewed relating to ventilation, health and school performance, 8 of them reported statistically significant improvements in respiratory health outcomes correlated with an increase in ventilation. These studies overall also found increased ventilation rates associated with higher student performance in reading and math.

Other studies have also found a positive relationship between building ventilation conditions and indoor and outdoor air quality with student performance. The findings of a study by Wargocki (2008) revealed an increase in school performance of 10–12-year-old children by 8-14% corresponding to a doubling of the ventilation rate. A study by Marcotte (2017) further shows how students may be affected by outdoor air pollution, performing worse on days with worse pollution. Another study found that a 1 standard deviation increase in PM 2.5 (particulate matter in the air less than 2.5 micrometers in diameter) on exam days is associated with a decline in student test performance of 3.9 percent of a standard deviation (Ebenstein et al., 2016). Another study using a difference-in-differences design found that attending schools less than a mile from toxic chemical sites decreases student test scores by 7 to 9 percent of a standard deviation (Rau et al., 2015). Persico and Venator (2021) studied cumulative effects of students' continued exposure to pollution due to proximity to a pollutant site and found such a site operating within one mile of a school is associated with lower test scores of approximately 2.4 percent of a standard deviation. The effect was worse on test scores of younger students and in the case of longer cumulative exposure.

Other intervention studies also found statistically significant increases in school performance rates correlated with increased ventilation rates (Fisk, 2017). A more recent study by Roth (2020) calculates the causal effect of indoor air quality of test days on student performance and shows that even installing air filters on only the test day would raise test scores by .09 percent of a standard deviation. Similarly, Gilraine (2020) found that the presence of air filters in classrooms raised mathematics scores by 0.20 percent of a standard deviation, and the improvement continued through to the following year. Most recently, Biasi et al. (2024) revealed that financing HVAC improvements through authorizing a relevant bond would increase test scores by over 0.20 standard deviations over 3-6 years. Furthermore, they concluded that removing the spending gap between high and low SES districts and investing those additional funds in HVAC improvements could close the initial test score gap by up to 25%.

Classroom temperature can also have an impact on learning. A study by Park et al. (2020) found a significant causal relationship between temperature and academic learning, with 1° F hotter days reducing annual learning by 15%. Heat disproportionately affected racial minority students, accounting for 5% of the racial achievement gap. The study findings also showed that cumulative learning impacts may be mitigated through effective air conditioning and that environmental temperature is a meaningful contributor to racial and geographic gaps in learning achievement. Extreme temperatures, either in the summer or the winter, seem to have substantial effects on student academic performance, with the impacts larger among students in relatively lower SES (Carlson & Shepardson, 2024; Roach & Whitney, 2022; Johnston et al., 2021). Carlson and Shepardson (2024) showed that while test day temperature does not have any significant effect on student performance, long term temperature changes, especially in the summer, has substantial effects on student performance, especially in math and slightly less so in reading. The difference in average academic performance between highest and lowest temperature in a 90-day period is two percentiles in the summer and only about one percentile in the winter. However, Roach and Whitney (2022) showed that in relatively cooler average high temperatures, heat is associated with disproportionately large reductions in math and reading outcomes. For students more acclimatized to hot temperatures in Australia, a different study showed cold weather had negative impacts on student test scores, but again test day weather had no effect (Johnston et al., 2021)

Although recent studies in economics suggest that air quality and environmental factors influence student learning outcomes, none other than the Biasi et al. (2024) study of HVAC system financial investments have looked specifically at HVAC systems within schools. Of the other studies that did examine directly the link between HVAC conditions and student outcomes (many summarized in Fisk, 2017), all to our knowledge have relied on small samples and/or cross-sectional correlational designs. This type of research design may generate misleading findings since well-resourced schools likely have more modern and better maintained facilities, and also likely host more economically advantaged students with higher average test scores. Our study seeks to provide new evidence on this topic using a panel dataset of detailed building inspections to estimate the effects of within-school changes in HVAC system conditions on student attendance, learning, and behavior.

Methods

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 ventilation and student absenteeism, behavior, and learning. In particular, we extract data from the New York Building Conditions Surveys (BCS) reports in 2005, 2010, and 2015 to learn about school building conditions over time, including cooling, heating, and ventilation systems. Additionally, we utilize reconstruction and replacement information in BCS reports in 2020, 2021, and 2022 to update the year of reconstruction and replacement.[1,2] Not all schools were surveyed in the exact survey years and school years can vary within calendar years. 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 buildings, which are not used for instructional purposes, and approximately 600 buildings, which do not clearly match schools in the education data. Our final sample retains around 2,600 buildings per year from 2006-06 to 2018-19 for our analysis.

We utilize 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 as an order of Excellent, Satisfactory, Unsatisfactory, Non-functional, and Critical Failure. 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. 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

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[1] 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.

[2] School districts with relatively poor building conditions, which are more likely to undergo reconstruction or replacement, were scheduled for the earlier years of the survey term. Therefore, updating this information using the latest BCS data is valuable, even if it does not cover all school buildings.

HVAC system is rated either as unsatisfactory (non-existent, non-functional, or unsatisfactory) or satisfactory (satisfactory or excellent). In the usage of 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 fragile, but we expect that any changes in HVAC system condition between survey years will bias our results downwards because of the imputation. (We confirm that this is the case with 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.) In addition to the overall system conditions, we use the year of the last major system reconstruction or replacement to examine the effects of reported improvements to cooling, heating, and ventilation systems.

To examine the importance of HVAC system quality for student outcomes, we employ four outcome measures: (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 or comfort 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 accountability measures annually. Student absenteeism rates are calculated by subtracting the percent of school days in attendance from 100 percent. Suspension rates are calculated as the number of students receiving an out-of-school suspension per 100 students. Reading and math test scores from grades 3 to 8 are first standardized by grade, subject, and year. We then obtain 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 add counts of the number of hot (over 30 degrees Celsius) and number of cold (under 0 degrees Celsius) days during the school year based on daily temperature data from the National Climate Data Center via the R package rnoaa. We also extract air pollution data from NASA's Socioeconomic Data and Applications Center to calculate average PM 2.5 air pollution (particular matter under 2.5 micrometers) at the nearest measurement site. These data values serve as supplementary environmental information and are not directly used in the main analysis.

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 2,830 schools with 33,778 school-year observations. We report descriptive statistics on the full sample in Table 1. Of note, the average school in our sample has an absenteeism rate of 5.3 percent of school days, suspension rate of 4.2 suspensions per 100 students, and test scores slightly higher than the state mean. 84 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. 54 percent of our sample is elementary schools, 17 percent middle schools, 20 percent high schools, and 5 percent other grade configurations. The majority of schools are located in non-urban settings: 46 percent in suburbs, 24 percent in rural locales, 12 percent in towns, and 8 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 general, our sample closely mirrors demographics from the state of New York outside of New York City.

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 ventilation systems over time, sometimes even leading an HVAC system to become non-functional or go into critical failure. Second, we can observe ventilation 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 A1, 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:

$$Y_{it} = \beta_0 + C_{it}'\beta_1 + X_{it}'\beta_2 + \gamma_i + \delta_t + \varepsilon_{it} \qquad (1)$$

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. In doing so, this approach assumes that within-school changes in HVAC system condition are unrelated to unobserved time-varying components of the error term. We use cluster-robust standard errors at the school level to account for serial correlation.

For each type of HVAC system (cooling, heating, and ventilation), we also know the exact date of system reconstructions or replacements. Therefore, we can use these dates to conduct difference-in-differences-style estimation of the effects of HVAC system replacement on subsequent student outcomes. Between 2006 and 2019, we observe 1,283 cooling system reconstructions or replacements, 1,273 heating system reconstructions or replacements and 1,323 ventilation system reconstructions or replacements, occurring in the sample of school buildings.

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 these empirical issues associated with two-way fixed effects, 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 attempts to mitigate any parallel trend issues through the use of inverse probability weighting based on control variables. Using the same control variables as in equation 1, the doubly robust estimator thereby permits a weaker version of the parallel trends assumption – that the parallel trends assumption holds *conditional on observed covariates*. We also 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.

Results

Exposure to Poor HVAC System Conditions

Over the period 2006 through 2019, only 4 percent of students in our sample attended school building facilities rated in excellent condition overall in their most recent building inspection reports. 77 percent of students attended school buildings rated as satisfactory, and 20 percent of students attended school buildings rated overall as unsatisfactory. These figures look worse for free or reduced-price lunch eligible students, of whom 23 percent attend school buildings rated overall as unsatisfactory (Figure 1). Black students, Hispanic students, and other race/ethnicity students all also are more likely to attend a school with the main instructional building in unsatisfactory condition than are White students (Figure 2). These gaps could reflect differences in the amount of resources schools have available for upkeep, maintenance, and new construction, or they could merely reflect differences in the age of the buildings. We observe that schools with higher proportions of students eligible for free or reduced-price lunch are located, on average, in buildings with earlier construction years. (The full distribution of school building age is plotted in Appendix Figure A2.)

This variation in exposure to poor building conditions overall translates into similar variation in exposure to poor HVAC system conditions. Cooling system conditions look on average fairly similar across student groups, with a total of 15 percent of students in schools with unsatisfactory or non-functional heating systems. Some inequities appear for heating systems, where only 7 percent of White students but 10 percent of Black and Hispanic students attend schools with inadequate heating systems. 15 percent of students also attend schools with unsatisfactory or non-functional ventilation systems, but this value is higher for free or reduced-price eligible students at 16 percent and for Black and Hispanic students at 18 percent. Based on these descriptive patterns, if we do discover that poor conditions of HVAC systems have a detrimental impact on student attendance, learning, or behaviors, then these adverse effects would be disproportionately borne by lower-income, Black, and Hispanic students in New York.

The consequences of HVAC system conditions may vary depending on the environmental context of the school. For instance, non-functioning cooling systems may matter more in hot regions of the state; non-functioning heating systems may matter more in cold regions of the state; and poor ventilation systems may matter more in high-pollution regions. In Figures 3 through 5, we explore the environmental conditions of schools with unsatisfactory HVAC systems in the most recent year of our data (2019). Figure 3 shows that schools with unsatisfactory cooling systems are spread across the state, including many in the downstate regions that experienced a high number of hot days in 2019. In Figure 4 we observe that most schools with unsatisfactory heating systems are located in the coldest upstate regions of the state. Finally, we see in Figure 5 that schools with poor ventilation systems are concentrated in urban areas such as NYC and Buffalo, with high air pollution as measured by PM 2.5 levels. In sum, we hypothesize that these non-functional HVAC systems could have real consequences for student health, comfort, and concentration, given the underlying environmental conditions surrounding the schools.

Effects of HVAC System Condition Changes on Student Outcomes

We first seek to learn the effects of changes in cooling, heating, and ventilation system conditions on student absenteeism and suspension. Table 2 presents these results with separate two-way fixed effect regressions for each HVAC system type.[3] The coefficient estimates on satisfactory system condition represent estimated differences between satisfactory or excellent HVAC systems and unsatisfactory or non-functional or non-existent systems. Column 1 of Table 2 shows a marginally significant student absence decrease of 1.2 percent ($p<0.1$) when cooling systems change from unsatisfactory to satisfactory condition, a decrease of 3 percent ($p<0.05$) when heating systems change from unsatisfactory to satisfactory condition, and a decrease of 2 percent ($p<0.05$) when ventilation systems change from unsatisfactory to satisfactory condition.[4] Column 2 shows a 6 percent decrease ($p<0.01$) in student suspension from satisfactory heating system conditions, and a 7 percent decrease ($p<0.01$) in student suspension from satisfactory ventilation system conditions. Satisfactory cooling system conditions have no significant impact on student suspension. Overall, particularly for heating and ventilation systems, within-school deterioration in system condition appears to increase student absence and student suspension from school.

Columns 3 and 4 of Table 2 present the corresponding estimates for effects of school HVAC system conditions on student test scores in reading and math. For heating, cooling, and

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[3] Our preference is to not include all system type conditions in the same regression due to high correlation among them. However, we have also run these regressions with all three HVAC system condition variables included simultaneously. These results are described in the robustness tests section and are qualitatively similar.

[4] Because the table presents incidence rate ratios for student absence and suspension, an incident rate ratio of 0.9 represents a reduction of 10 percent in the outcome, and an incident rate ratio of 1.1 represents an increase of 10 percent in the outcome. In the text we therefore present the corresponding percent changes in the outcome instead of the raw incidence rate ratio.

ventilation systems, students perform approximately 0.02 to 0.03 standard deviations better in reading under satisfactory or excellent system conditions when compared to unsatisfactory or non-functional system conditions. However, only the cooling system effect is statistically significant ($p<0.05$). In math, students also perform around 0.03 standard deviations better under satisfactory ventilation system conditions (marginally significant at $p<0.1$) and 0.05 standard deviations better under satisfactory heating system conditions ($p<0.05$). According to our model, changes in cooling system conditions have no significant effect on math scores, however. Although these effects are modest in magnitude – corresponding to approximately one-tenth of average annual test score gains (Hill et al., 2007) – together they suggest an important connection between HVAC system conditions and the learning environment.

We have shown that within-school changes in HVAC system condition over time result in changes to student absence rates, suspension rates, and test performance. Theoretically, these effects could arise through a variety of mechanisms. First, improvements in school ventilation system conditions could reduce the spread of infectious diseases within schools (Lindsley et al., 2021), thereby decreasing missed days of school due to sickness. Second, improvements in heating or cooling system conditions could enhance temperature control within schools, thereby making the school building a more comfortable environment in which to learn (Park et al., 2020). Similarly, more comfortable temperatures could help to prevent student misbehavior, given the well-known link between, for instance, heat and criminal behavior (Cohen & Gonzalez, 2024). Third, better school ventilation systems could improve air quality within schools, mitigating the negative effects of poor air quality on student health and learning (Ebenstein et al., 2016; Gilraine, 2020; Persico & Venator, 2021). Because we cannot measure actual disease spread or temperature changes within schools, we cannot test directly for the first or second mechanism.

We do, however, have a subjective measure of indoor air quality within schools from the building inspection. Appendix Table A2 shows that, indeed, changes in school HVAC system conditions lead to changes in indoor air quality. Satisfactory cooling system conditions increase the likelihood of 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 this likelihood by 12 percentage points. At least in part, indoor air quality appears to mediate the relationship between HVAC system conditions and student outcomes.

Effects of HVAC System Reconstructions or Replacements on Student Outcomes

The changes in school HVAC system conditions we observe between 2006 and 2019 (summarized descriptively in Appendix Table A1) could arise either due to deterioration in these systems over time or due to upgrades or replacements of the systems. From the Building Conditions Survey, we have information on the date of most recent cooling, heating, and ventilation system reconstructions and replacements. As described in the methods section, we can therefore use a modified difference-in-differences approach to estimate effects of these reconstructions/replacements on school and student outcomes. These are presented in Table 3.

First, looking at cooling system reconstructions and replacements, we see no significant effect on absence, suspension, or reading scores. However, we do observe an increase in math test scores of 0.03 standard deviations following cooling system replacement. This is consistent with prior evidence that air conditioning systems help to 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 does have a positive impact on math scores with a magnitude of 0.04 standard deviations. Ventilation system reconstructions and replacements have on average no effect on any of the academic or behavioral outcomes.

Because of the sensitivity of student math performance in particular to cooling and heating system replacements, we further present full CSDID event study estimates of math scores for eight years prior to and eight years following HVAC system replacement in Figure 6. As can be seen in both panels (a) and (b), math score time trends were relatively flat prior to cooling and heating system replacement before trending clearly upwards following system replacement. The same general pattern emerges for math scores in response to ventilation system replacement (panel c), but this change is not statistically significant. CSDID event studies for all other outcomes are provided in Appendix Figure A3 (absence), A4 (suspension), and A5 (reading scores). We do not uncover any visual evidence of pretreatment parallel trend violations across any of the outcomes or system type replacements.

Robustness Tests

We conduct several sensitivity tests to assess the robustness of our findings regarding HVAC system conditions and student academic and behavioral outcomes. First, one might have concerns that changes to HVAC system conditions occur at the same time as other school construction or renovation, which could have a variety of impacts on students. We therefore replicate our system condition regressions controlling for two additional control variables, one an indicator variable that equals one if the school experienced a major renovation that year (and zero otherwise), and the second a continuous variable of per-pupil construction outlay expenditures that year. See Appendix Table A3. All results remain practically identical.

Second, one may have concerns with our approach of assuming that HVAC system conditions remain constant between building condition survey years. We therefore replicate our main regressions and restrict the sample to only building condition survey years (Appendix Table A4). Although we lose some precision, the point estimates for the main findings are consistent. Specifically, we still see a significant decrease in absence, decrease in suspension, and increase in math scores from satisfactory heating systems. We do have one unusual finding in this alternative specification, which is that satisfactory cooling systems *increase* the incidence of student suspension by 4 percent.

We also perform these regressions including all system conditions as independent variables in the same model instead of in separate models (Table A5). Again, many of the same general findings remain: Satisfactory ventilation system conditions decrease absence and decrease suspension. Satisfactory heating systems reduce suspension and increase math scores. Satisfactory cooling system conditions, unexpectedly, increase the likelihood of suspension, but also increase reading performance. We anticipate some muting of the originally estimated effects occurs in this regression specification because of relatively high correlation across HVAC system conditions. Appendix Table A6 uses more detailed information from the building inspection reports, by separating HVAC system condition into three categories instead of two: (1) unsatisfactory or non-functional; (2) satisfactory; and (3) excellent. We find that our main results are driven by both within-school changes between satisfactory and unsatisfactory conditions and within-school changes between excellent and unsatisfactory conditions. We observe that student test scores are highest under excellent HVAC system conditions.

Finally, HVAC system condition changes can occur at any point during the study, which leads our treatment timing to mirror a “staggered adoption” setting. The Callaway and Sant’Anna approach used to estimate effects of HVAC system reconstructions and replacements wouldn’t work for system condition indicators, because treatment can turn on and off multiple times across the period. That is, there is no single treatment time per unit. For this reason, we instead use the de Chaisemartin and d'Haultfoeuille (2024) dynamic difference-in-differences estimator that accounts for potential bias from staggered treatment adoption but also allows treatment to turn on and off over time. The results, presented in Appendix Table A7, largely confirm the findings from our two-way fixed effects model, with significant decreases in student suspension and significant increases in math performance resulting from heating and ventilation system condition improvements. The directions of point estimates are consistent for student absence and reading scores, although they are not statistically significant in this model.

For the Callaway and Sant'Anna estimates of impacts of HVAC system reconstructions and replacements, we also conduct a sensitivity check that includes only never treated schools as comparisons instead of both never treated and not yet treated schools (Appendix Table A8). Results remain essentially identical as before, with significant increases of 0.04 standard deviations in math from both cooling and heating system reconstructions or replacements, and no other meaningful effects.

Discussion

Our study examines the role that school HVAC systems have played in shaping student behavioral and academic outcomes. Our findings indicate that HVAC system conditions indeed contribute significantly to school environments and student outcomes. Unsatisfactory or non-functional cooling, heating, and ventilation systems lead to 2 to 3 percent increases in student absenteeism rates.[5] Unsatisfactory or non-functional heating and ventilation systems also

[5] The main results in Table 2 are presented in terms of satisfactory condition effects on student outcomes (instead of unsatisfactory), and therefore go in the opposite direction. A supplementary

increase student suspension by over 6 percent. Unsatisfactory cooling systems reduce reading by 3 percent of a standard deviation, and unsatisfactory heating systems reduce math performance by 5 percent of a standard deviation.

Furthermore, students from low-income families and minoritized groups more frequently attend schools with poor HVAC system conditions. Changes in indoor air quality do appear to serve as an important mechanism in this link between HVAC system condition and student outcomes, although we cannot rule out other mechanisms such as less spread of contagious disease or more moderate classroom temperatures. Enhanced air quality could improve student attendance by decreasing the severity of asthma or reducing the likelihood of bronchitis (Beatty & Shimshack, 2011), for instance, which would reduce the number of students needing to stay home due to health conditions.

Our findings indicated no significant impacts of reconstructing or replacing a HVAC system on student attendance or behavior, but some positive impacts of reconstructing or replacing a HVAC system on student learning. We have two main theories for why this might be the case. First, we find that the within-school effects we uncover between HVAC conditions and student absence are driven primarily by system deterioration, not system improvements. Second, we note that HVAC system reconstruction/replacement occurs most frequently in schools that already have satisfactory or excellent systems in place. 75 percent of schools already have satisfactory or excellent cooling systems, 83 percent of schools have satisfactory or excellent heating systems, and 78 percent of schools have satisfactory or excellent ventilation systems, in

analysis split changes into condition improvements and condition deteriorations and found that condition deteriorations over time are largely driving our results more so than condition improvements.

the year prior to corresponding system reconstruction/replacement. For many schools, these appear to be routine updates that do not necessarily address underlying issues.

The data underlying this study has several limitations. For one, the building inspections did not occur on an annual basis for every school. This means that our main independent variables of interest (HVAC system conditions) have gaps between years. We have tested two approaches to dealing with this problem: (1) assuming that HVAC system conditions are constant between survey years; and (2) removing all school-year observations that do not correspond exactly to building conditions survey years. We find the same pattern of results across both methods, suggesting that this shortcoming in the data does not lead us to overall erroneous conclusions.

Another limitation is that some measures taken from the building conditions survey are necessarily subjective. That is, a ventilation system that is "unsatisfactory" to one building inspector might be "satisfactory" to a different building inspector. This certainly introduces some amount of measurement error in the HVAC system conditions variables (which would attenuate results if it represents classical measurement error). However, it is difficult to imagine a scenario in which this would introduce endogeneity. In order for this assessment to be correlated with the error term in a model with school and year fixed effects, there would need to be some *time-varying* unobservable factor that both affects the building inspector's assessment of a HVAC system condition and changes in student attendance, behavior, and learning patterns. It is difficult to envision this specific form of confounder.

A final limitation is that we do not observe directly student health conditions or school environmental conditions. We cannot know for sure, for instance, whether changes to quality of heating systems affects students through enhancements to student health or through temperature changes within the school or through some alternative mechanism. We also do not have further detail on why, or how, exactly HVAC system replacements and reconstructions took place. Future research could dig deeper into these specific pathways through which school building HVAC system condition might change and how such changes might affect students.

Many school districts across the country have used federal support funds received during the pandemic to invest in school capital improvements or more specifically to make upgrades to school HVAC systems. Under the American Rescue Plan Elementary and Secondary School Emergency Relief (ARP ESSER), 122 million USD has been disbursed to all 50 states, with the goal of helping schools to remain open and helping students recover academically from pandemic-induced learning loss. Existing data shows that around 40% of school districts planned to spend funds on HVAC improvement (US Department of Education, 2022). Our research suggests that this type of investment makes sense not only for public health crises such as the COVID-19 pandemic – but for the future health, well-being, and success of all students.

References

Alexander, D., & Lewis, L. (2014). Condition of America's Public School Facilities: 2012-13. First Look. NCES 2014-022. *National Center for Education Statistics*.

Beatty, Timothy K.M., and Jay P. Shimshack. 2011. "School Buses, Diesel Emissions, and Respiratory Health." *Journal of Health Economics* 30 (5): 987–99.

Belsha, K. (2024). COVID aid funded big repairs at high-poverty schools. Will that give academics a boost too? *Chalkbeat*. https://www.chalkbeat.org/2024/07/01/high-poverty-schools-spent-greater-share-of-covid-aid-on-buildings/

Biasi, B., Lafortune, J. M., & Schönholzer, D. (2024). What Works and for Whom? Effectiveness and Efficiency of School Capital Investments across the US (No. w32040). National Bureau of Economic Research.

Brooks. C. D., & Springer, M. G. (2024). ESSER-ting Preferences: Examining School District Preferences for Using Federal Pandemic Relief Fundings. Annenberg Institute EdWorkingPaper 24-913. https://doi.org/10.26300/mpm0-1a97

Callaway, B., & Sant'Anna, P. H. (2021). Difference-in-differences with multiple time periods. *Journal of econometrics*, *225*(2), 200-230.

Carlson, D, & Shepardson, A. (2024). Under the Weather? The Effects of Temperature on Student Test Performance. (EdWorkingPaper: 24-910). Retrieved from Annenberg Institute at Brown University: https://doi.org/10.26300/p9q4-jb65

Chiu, A., Lan, X., Liu, Z., & Xu, Y. (2023). What to do (and not to do) with causal panel analysis under parallel trends: Lessons from a large reanalysis study. *arXiv preprint arXiv:2309.15983*.

Cohen, F., & Gonzalez, F. (2024). Understanding the link between temperature and crime. *American Economic Journal: Economic Policy*, 16(2), 480-514.

De Chaisemartin, C., & d'Haultfoeuille, X. (2024). Difference-in-differences estimators of intertemporal treatment effects. *Review of Economics and Statistics*, 1-45.

Ebenstein, A., Lavy, V., & Roth, S. (2016). The long-run economic consequences of high-stakes examinations: Evidence from transitory variation in pollution. *American Economic Journal: Applied Economics*, *8*(4), 36–65.

Fisk, W. J. (2017). The ventilation problem in schools: literature review. In *Indoor Air* (Vol. 27, Issue 6, pp. 1039–1051). Blackwell Munksgaard. https://doi.org/10.1111/ina.12403

Gilraine, M. (2020). Air filters, pollution and student achievement. *Annenberg Institute at Brown University*.

Goodman-Bacon, A. (2021). Difference-in-differences with variation in treatment timing. *Journal of Econometrics*, *225*(2), 254-277.

Hill, C. J., Bloom, H. S., Rebeck Black, A., & Lipsey, M. W. (2007). Empirical Benchmarks for Interpreting Effect Sizes in Research. *MDRC Working Papers on Research Methodology*.

Hong, K., & Zimmer, R. (2016). Does investing in school capital infrastructure improve student achievement?. *Economics of Education Review*, *53*, 143-158.

Johnston, D. W., R. Knott, S. Mendolia, P. Siminski. 2021. Upside-Down Down-Under: Cold Temperatures Reduce Learning in Australia. Economics of Education Review, 85: 102172. https://doi.org/10.1016/j.econedurev.2021.102172

Lafortune, J., & Schönholzer, D. (2022). The impact of school facility investments on students and homeowners: Evidence from Los Angeles. *American Economic Journal: Applied Economics*, *14*(3), 254-289.

Lewis, K., & Kuhfeld, M. (2023). Education's long COVID: 2022-23 achievement data reveal stalled progress toward pandemic recovery. NWEA.

Lindsley, W. G., Derk, R. C., Coyle, J. P., Martin Jr, S. B., Mead, K. R., Blachere, F. M., Beezhold, D. H., Brooks, J. T., Boots, T., & Noti, J. D. (2021). Efficacy of portable air cleaners and masking for reducing indoor exposure to simulated exhaled SARS-CoV-2 aerosols—United States, 2021. *Morbidity and Mortality Weekly Report*, *70*(27), 972.

Lombardo, C. (2021). *Students Need To Be In Classrooms, With Masks, This Fall, Education Secretary Says*. https://www.northcountrypublicradio.org/news/npr/1022429844/students-need-to-be-in-classrooms-with-masks-this-fall-education-secretary-says

Marcotte, D. E. (2017). Something in the air? Air quality and children's educational outcomes. *Economics of Education Review*, *56*, 141–151.

Mendell, M. J., Eliseeva, E. A., Davies, M. M., Spears, M., Lobscheid, A., Fisk, W. J., & Apte, M. G. (2013). Association of classroom ventilation with reduced illness absence: A prospective study in California elementary schools. *Indoor Air*, *23*(6), 515–528. https://doi.org/10.1111/ina.12042

Milton, D. K., Glencross, M., & Walters, M. D. (2000). *Risk of Sick Leave Associated with Outdoor Air Supply Rate, Humidification, and Occupant Complaints.*

Nowicki, J. M. (2020). K-12 Education: School Districts Frequently Identified Multiple Building Systems Needing Updates or Replacement. Report to Congressional Addressees. GAO-20-494. *US Government Accountability Office*.

Park, R. J., Goodman, J., Hurwitz, M., & Smith, J. (2020). Heat and learning. *American Economic Journal: Economic Policy*, *12*(2), 306–339. https://doi.org/10.1257/POL.20180612

Persico, C. L., & Venator, J. (2021). The effects of local industrial pollution on students and schools. *Journal of Human Resources*, *56*(2), 406–445.

Petrov, O. (2024). Impact of Indoor Air Quality on Health: Analyzing HVAC System Performance. *Innovative Engineering Sciences Journal*, *4*(1).

Rambachan, A., & Roth, J. (2023). A more credible approach to parallel trends. *Review of Economic Studies*, *90*(5), 2555-2591.

Rau, T., Urzúa, S., & Reyes, L. (2015). Early exposure to hazardous waste and academic achievement: Evidence from a case of environmental negligence. *Journal of the Association of Environmental and Resource Economists*, *2*(4), 527–563.

Roach, T., & Whitney, J. (2022). Heat and learning in elementary and middle school. Education Economics, 30(1), 29-46.

Roth, S. (2020). *The effect of indoor air pollution on cognitive performance: Evidence from the UK*. Mimeo.

Sant'Anna, P. H., & Zhao, J. (2020). Doubly robust difference-in-differences estimators. *Journal of econometrics*, *219*(1), 101-122.

Seppänen, O., Fisk, W., 2002. Association of ventilation system type with SBS symptoms in office workers. Indoor Air 12 (2), 98–112.

Seppänen, O. A., Fisk, W. J., & Mendell, M. J. (1999). Association of ventilation rates and CO2 concentrations with health and other responses in commercial and institutional buildings. *Indoor Air*, *9*(4), 226–252.

Shendell, D. G., Prill, R., Fisk, W. J., Apte, M. G., Blake, D., & Faulkner, D. (2004). Associations between classroom CO2 concentrations and student attendance in Washington and Idaho. *Indoor Air*, *14*(5), 333–341.

Silberstein, K., & Roza, M. (2024). The Massive ESSER Experiment: Here's what we're learning. *Education Next*, 24(4). https://www.educationnext.org/the-massive-esser-experiment-heres-what-were-learning/

Simons, E., Hwang, S.-A., Fitzgerald, E. F., Kielb, C., & Lin, S. (2010). The impact of school building conditions on student absenteeism in upstate New York. *American Journal of Public Health*, *100*(9), 1679–1686.

Tashtoush, B., Molhim, M., & Al-Rousan, M. (2005). Dynamic model of an HVAC system for control analysis. *Energy*, *30*(10), 1729-1745.

Teculescu, D. B., Sauleau, E.-A., Massin, N., Bohadana, A. B., Buhler, O., Benamghar, L., & Mur, J.-M. (1998). Sick-building symptoms in office workers in northeastern France: a pilot study. *International Archives of Occupational and Environmental Health*, *71*(5), 353–356.

U.S. Department of Education. (2022). *U.S. Department of Education Announces Distribution of All American Rescue Plan ESSER Funds and Approval of All 52 State Education Agency Plans*. Press Release, Office of Communications and Outreach.

Wargocki, P. (2008). *Improving indoor air quality improves the performance of office work and school work and provides economic benefits*. https://www.researchgate.net/publication/287394666

Tables and Figures

Figure 1. Exposure to Unsatisfactory HVAC Conditions by Student Economic Status

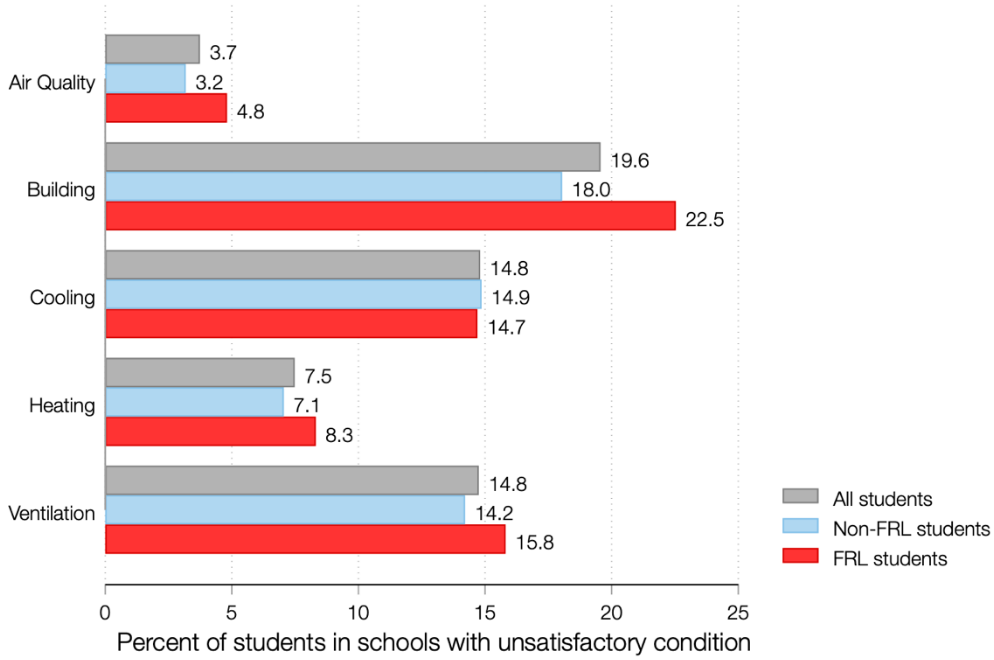


Figure 2. Exposure to Unsatisfactory HVAC Conditions by Student Race/Ethnicity

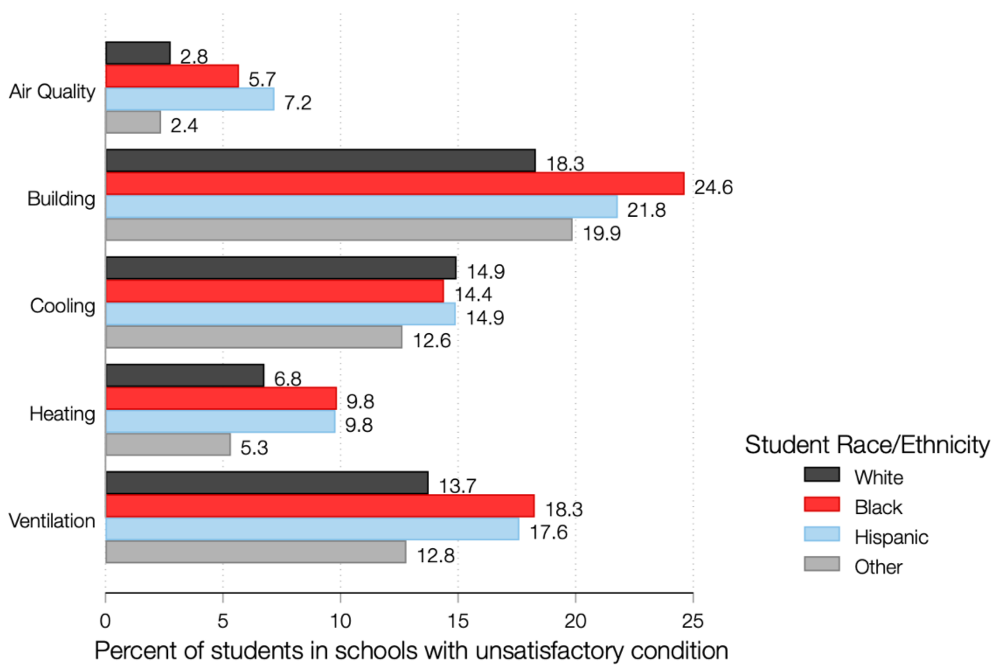
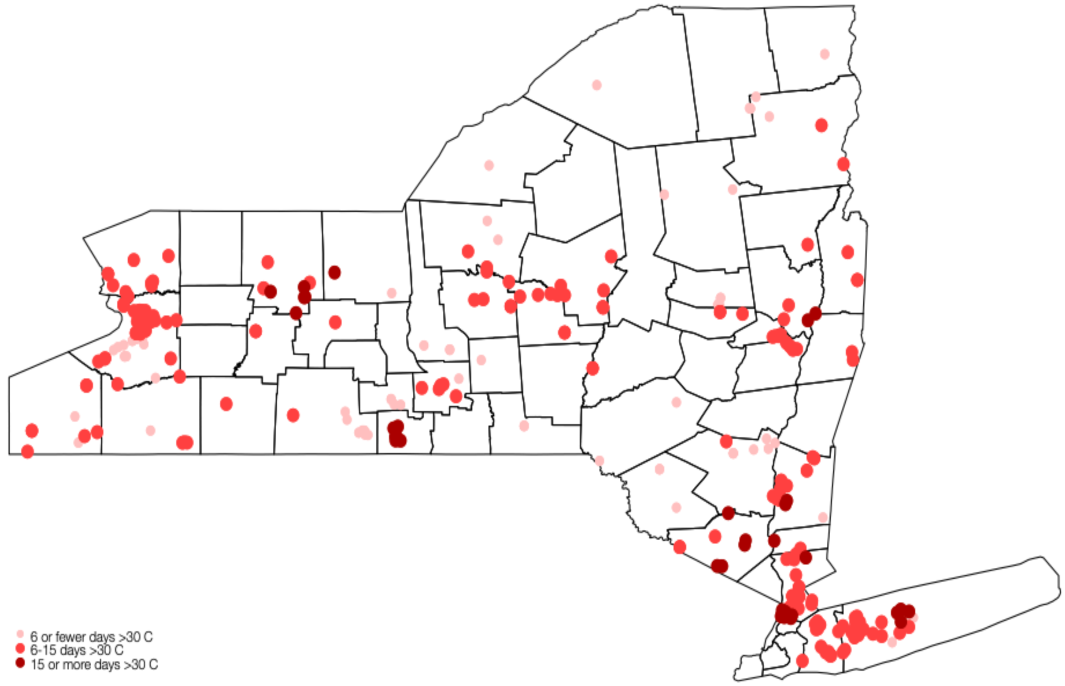
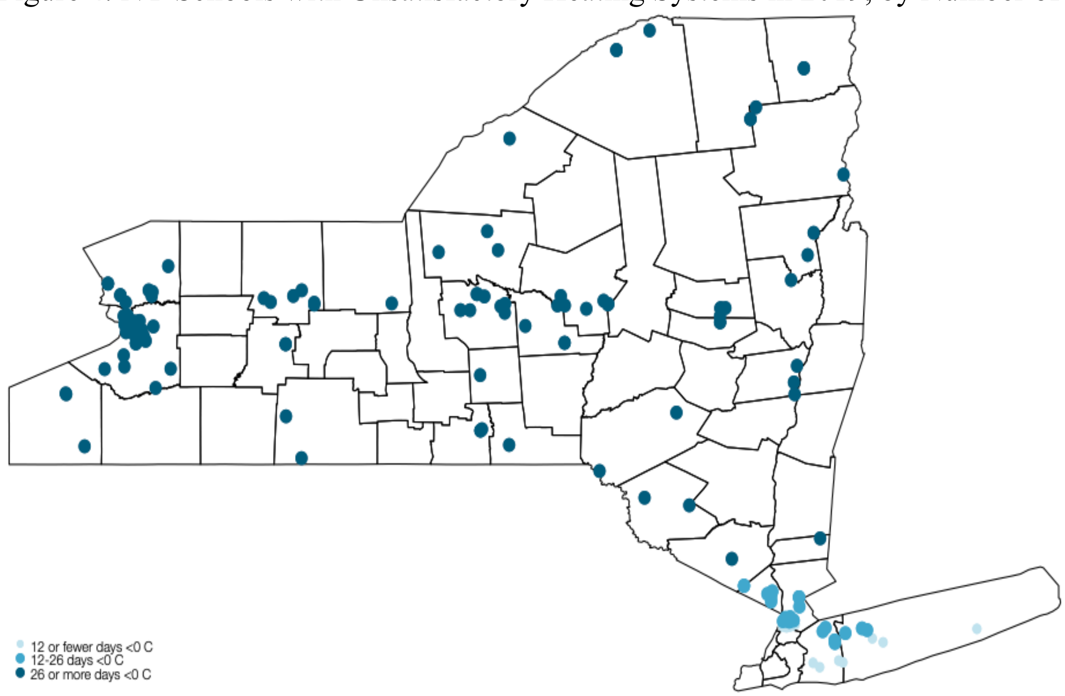


Figure 3. NY Schools with Unsatisfactory Cooling Systems in 2019, by Number of Hot Days



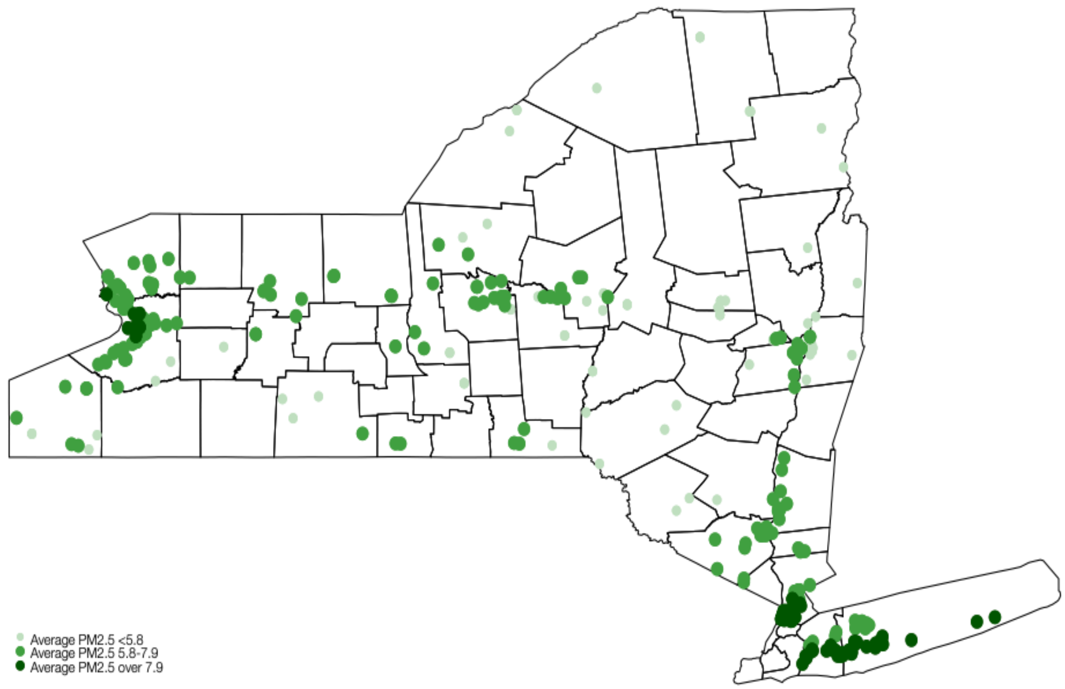
Note. Schools marked in dark red had 15 or more days, schools in medium red had 6-15 days, and schools in light red had 6 or fewer days with temperature over 30 degrees Celsius in the 2018-2019 school year.

Figure 4. NY Schools with Unsatisfactory Heating Systems in 2019, by Number of Cold Days



Note. Schools marked in dark blue had 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.

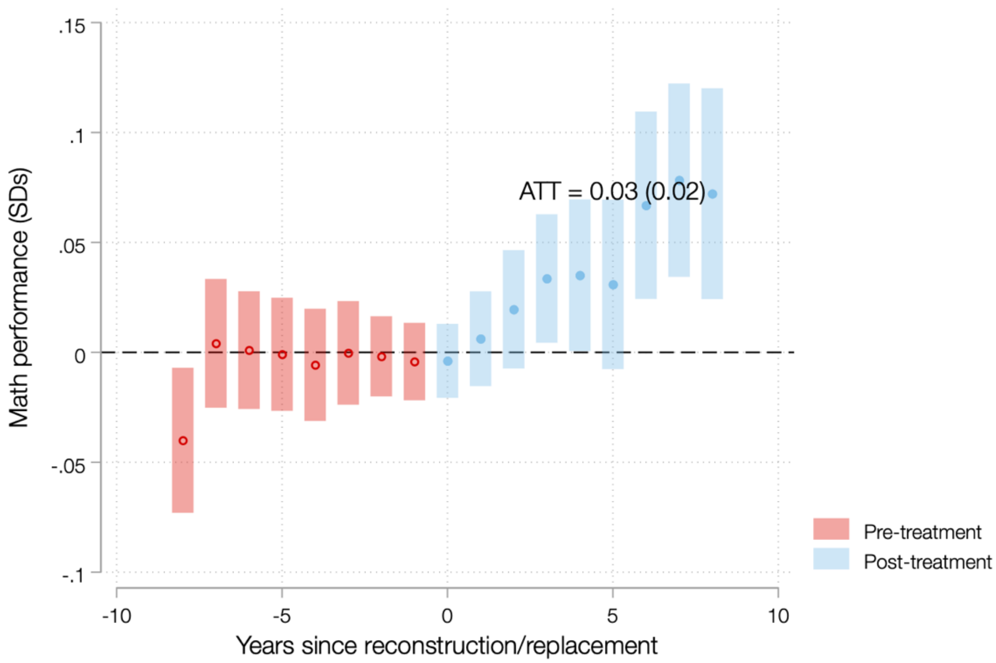
Figure 5. NY Schools with Unsatisfactory Ventilation Systems in 2019, by Air Pollution Levels



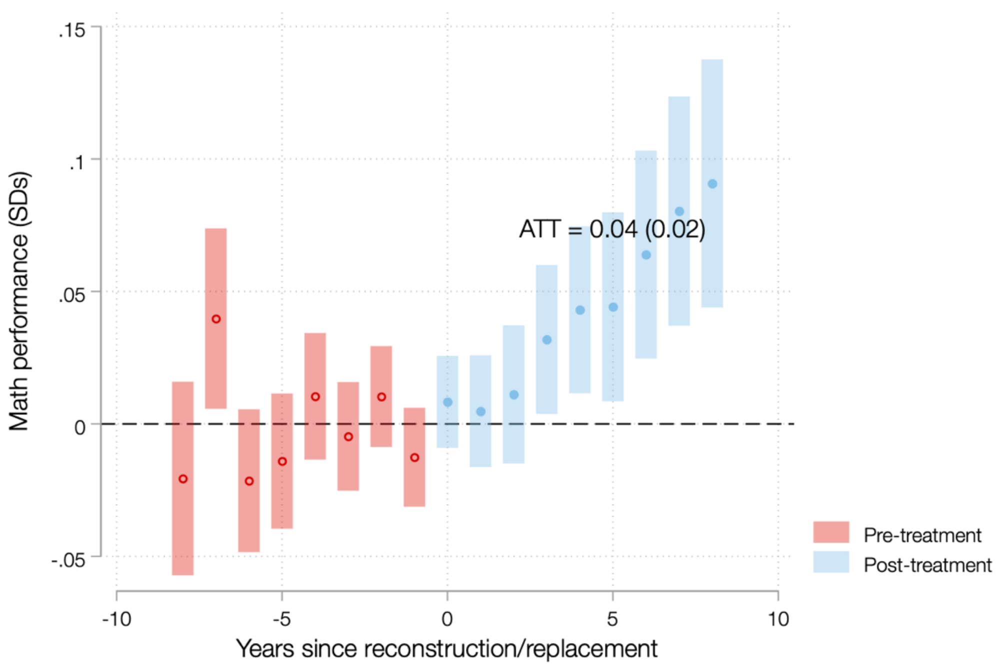
Note. Schools marked in dark green had average PM2.5 levels of over 7.9, schools marked in medium green had average PM2.5 levels of between 5.8 and 7.9, and schools marked in light green had less than 5.8 average PM2.5 levels in the 2015-2016 school year.

Figure 6. Event Studies of HVAC System Reconstruction/Replacement and Student Math Scores

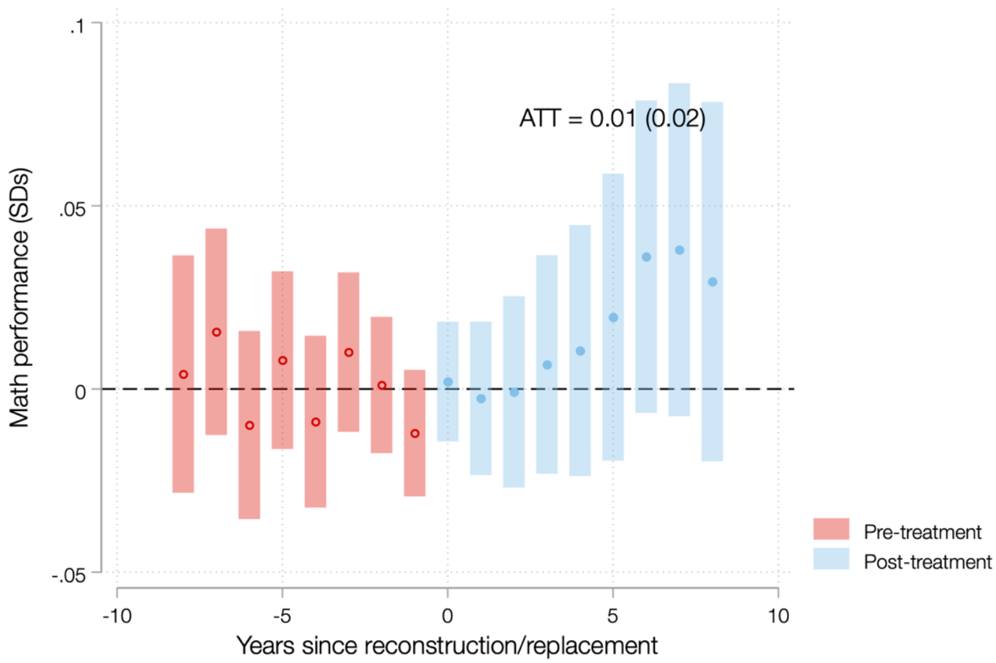
(a) Cooling System



(b) Heating System



(c) Ventilation System



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.

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

Variable	Mean or Proportion	Standard Deviation
Outcomes		
Percent of days absent	5.34	4.50
Suspensions per 100 students	4.23	6.91
Reading performance (SDs)	0.11	0.94
Math performance (SDs)	0.08	0.93
Building and environmental conditions		
Cooling system condition satisfactory	0.84	NA
Heating system condition satisfactory	0.93	NA
Ventilation system condition satisfactory	0.86	NA
Indoor air quality satisfactory	0.82	NA
Overall building condition satisfactory	0.72	0.45
Years remaining heating system	17.07	11.23
Years remaining cooling system	14.33	9.15
Years remaining ventilation system	12.21	10.41
Building construction year	1953.76	19.49
Major renovation past year	0.48	0.50
Days below 0 degrees Celsius	33.36	18.42
Days above 30 degrees Celsius	8.30	5.45
Average PM2.5 pollution	8.20	1.87
School characteristics		
Elementary school	0.54	NA
Middle school	0.17	NA
High school	0.20	NA
Other grade configuration	0.05	NA
City locale	0.08	NA
Suburb locale	0.46	NA
Town locale	0.12	NA
Rural locale	0.24	NA
Student enrollment	574.98	375.48
Pupil-to-teacher ratio	13.36	4.03
Construction outlay per pupil ($)	13,512.46	50,306.73
Percent students free/reduced price lunch	35.18	25.19
Percent students White	71.62	28.52
Percent students Black	10.08	16.90
Percent students Hispanic	11.96	16.09
Percent students Asian	3.94	6.15
Percent students multiracial	1.69	3.15

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

	Absence (IRR)	Suspension (IRR)	Reading (SDs)	Math (SDs)
Cooling system satisfactory	0.9840+	1.0148	0.0291*	0.0081
	(0.009)	(0.012)	(0.012)	(0.014)
Heating system satisfactory	0.9719*	0.9384**	0.0247	0.0461*
	(0.012)	(0.014)	(0.019)	(0.019)
Ventilation satisfactory	0.9794*	0.9317**	0.0216	0.0289+
	(0.009)	(0.010)	(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	33,778	31,535	28,609	28,609
Schools	2,830	2,678	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

	Absence (Per 100)	Suspension (Per 100)	Reading (SDs)	Math (SDs)
Cooling system replacement	0.0199	0.1943	0.0059	0.0327*
	(0.142)	(0.136)	(0.015)	(0.016)
Heating system replacement	-0.0562	-0.0617	0.0110	0.0408**
	(0.121)	(0.119)	(0.014)	(0.016)
Ventilation replacement	-0.0588	-0.0078	0.0083	0.0119
	(0.140)	(0.127)	(0.015)	(0.017)
Estimator	CSDID	CSDID	CSDID	CSDID
Controls	Yes	Yes	Yes	Yes
Observations	33,778	31,535	28,609	28,609
Schools	2,830	2,678	2,310	2,308

+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

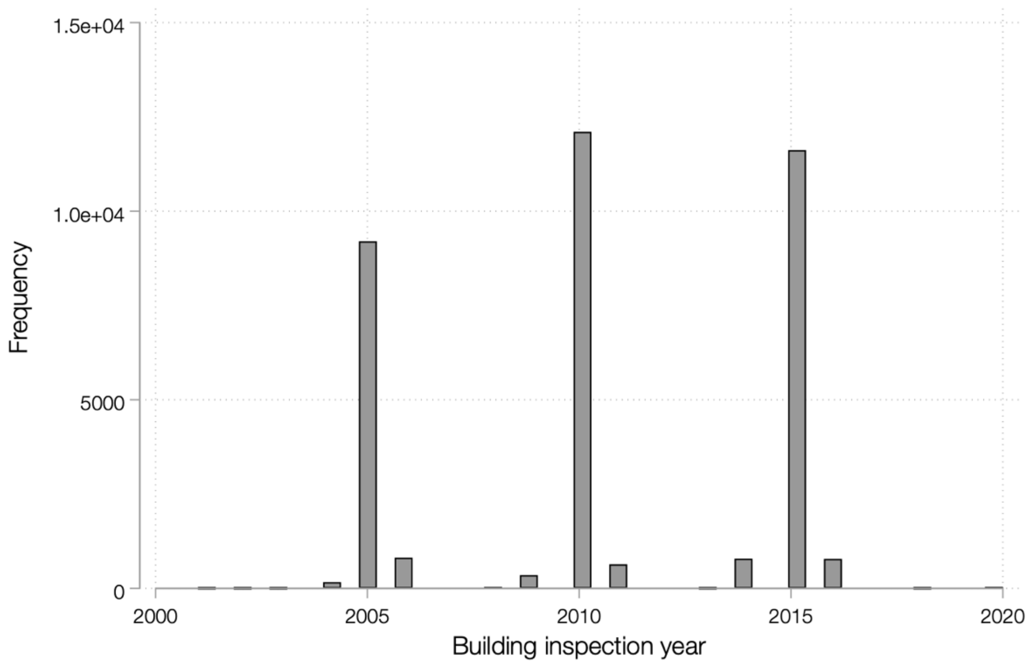


Figure A2. Histogram of School Building Construction Year

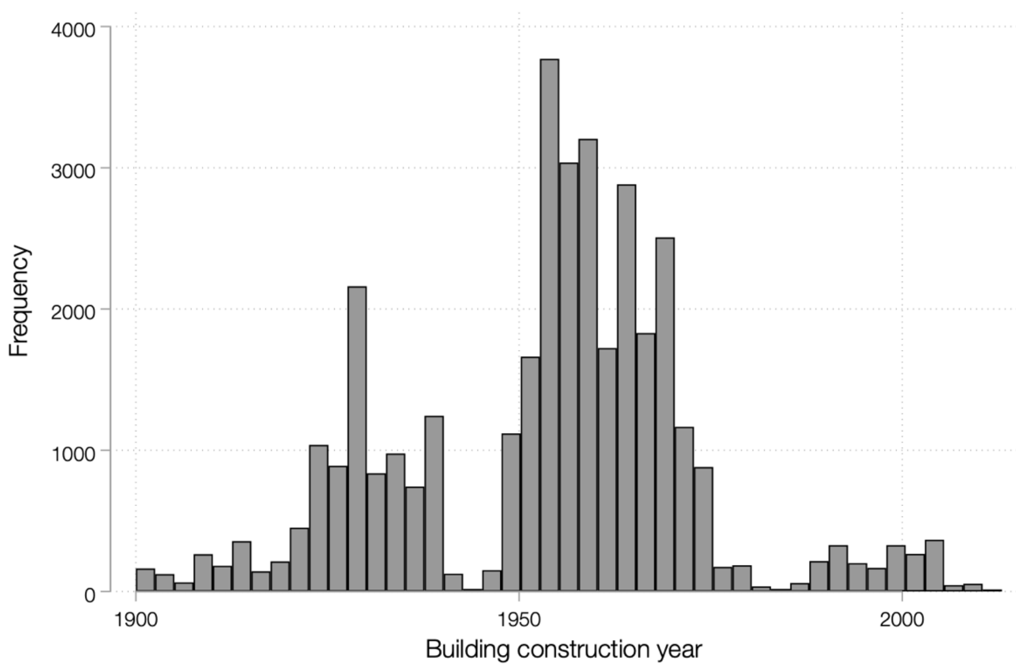
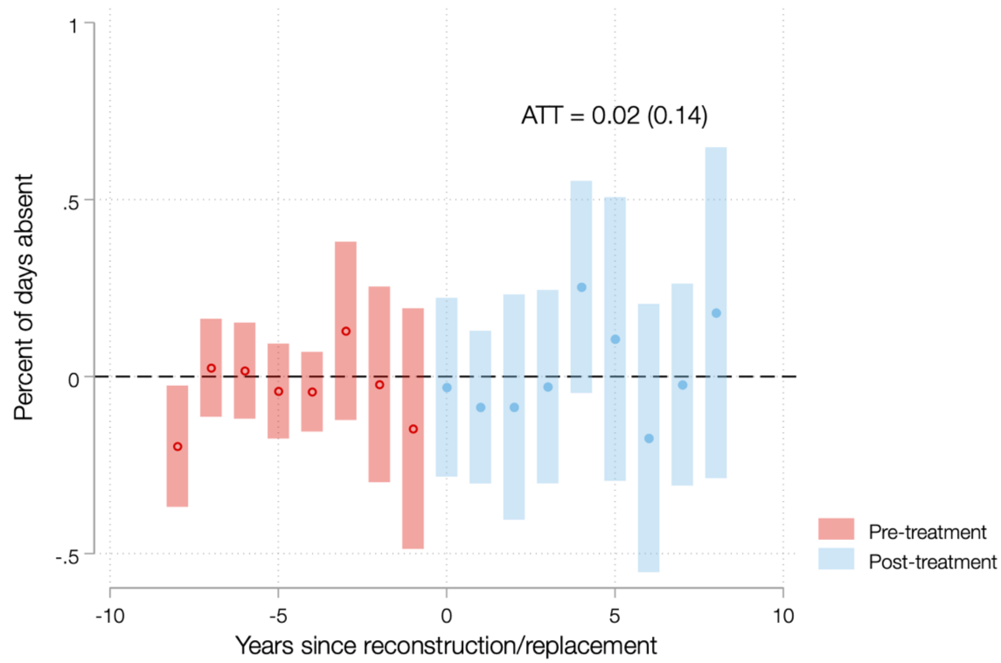
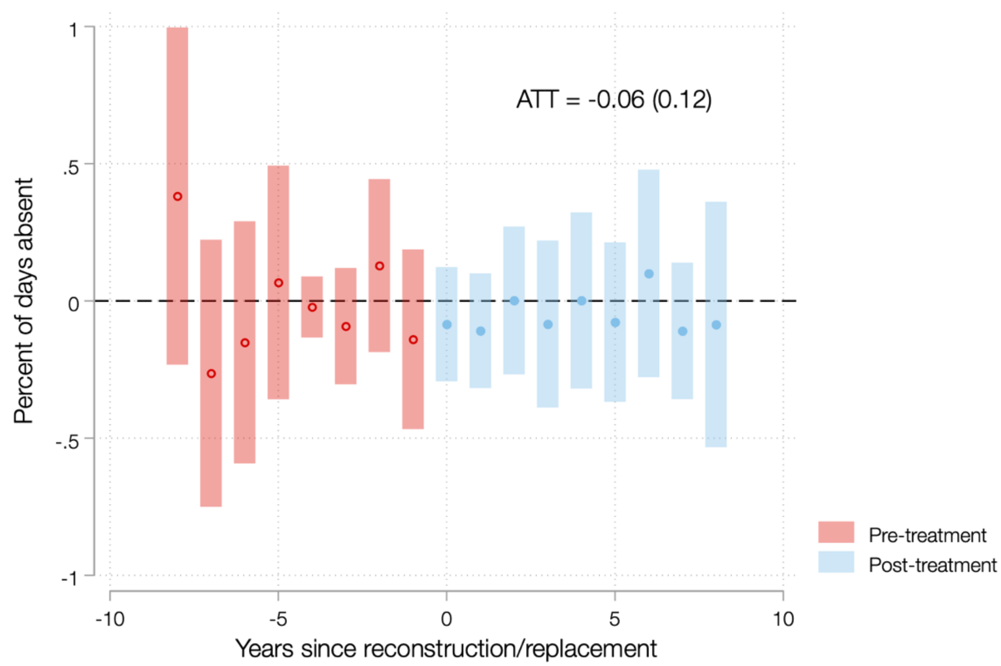


Figure A3. Event Studies of HVAC System Reconstruction/Replacement and Student Absence

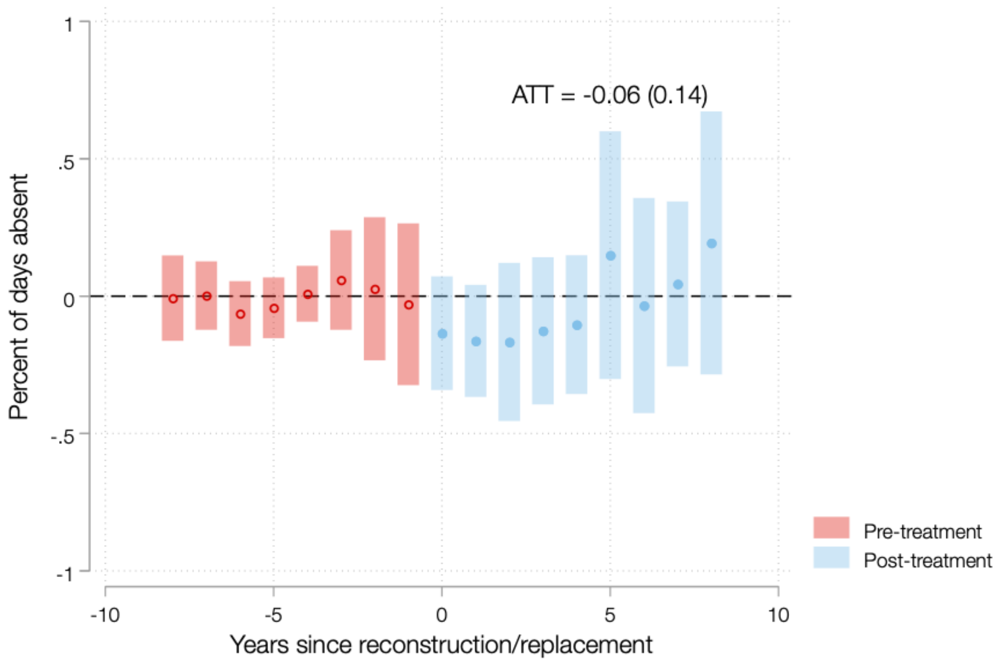
(a) Cooling System



(b) Heating System



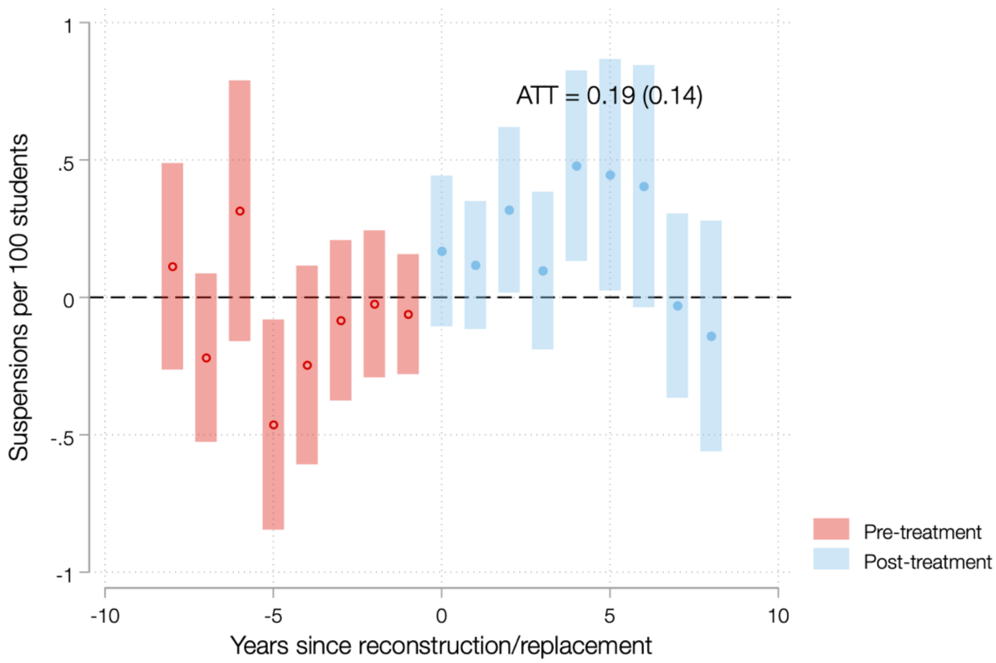
(c) Ventilation System



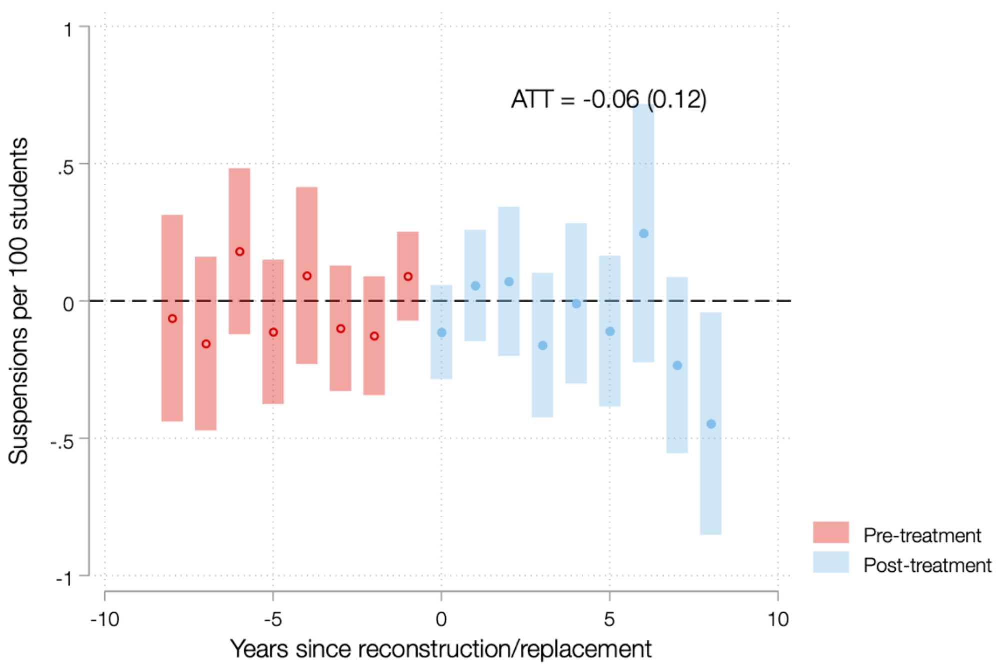
Note. All event studies above come from the Callaway and Sant'Anna (2021) doubly robust difference-in-differences estimator, with stabilized inverse probability weighting based on baseline covariates of pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students 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.

Figure A4. Event Studies of HVAC System Reconstruction/Replacement and Suspension Rate

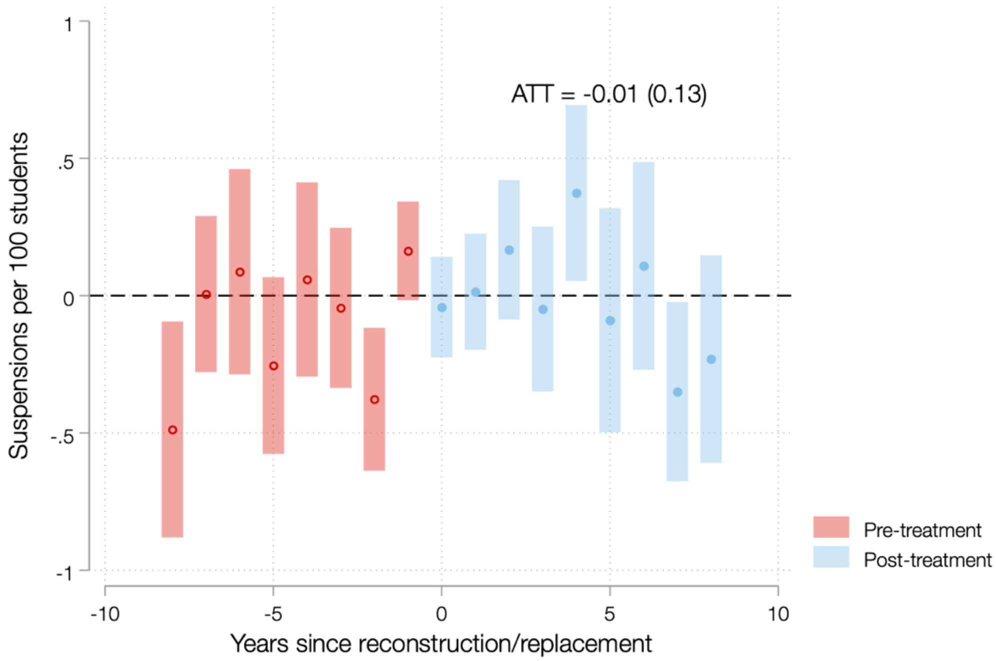
(a) Cooling System



(b) Heating System



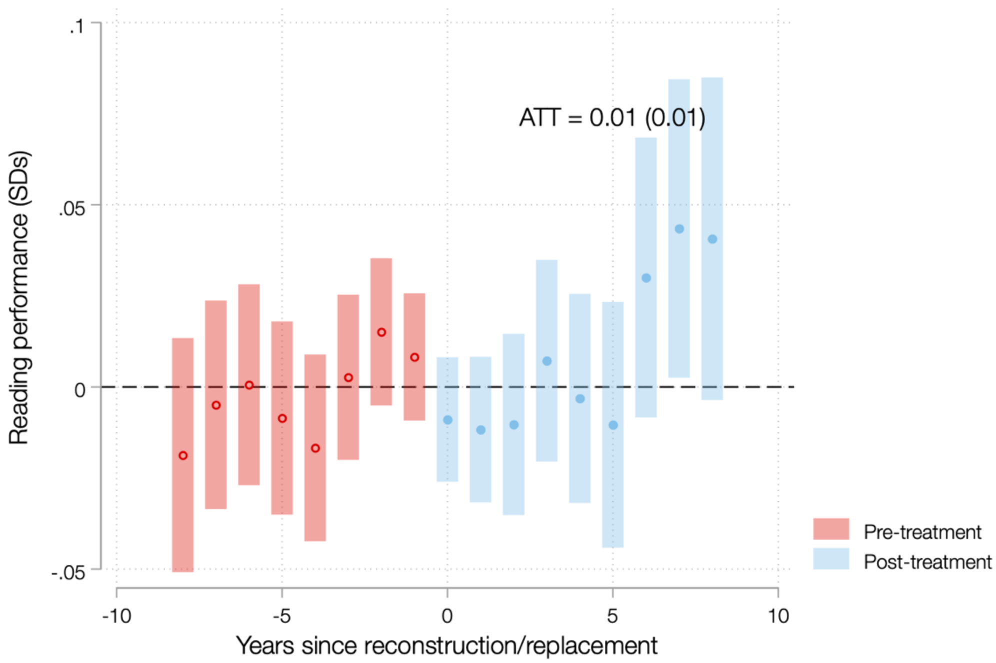
(c) Ventilation System



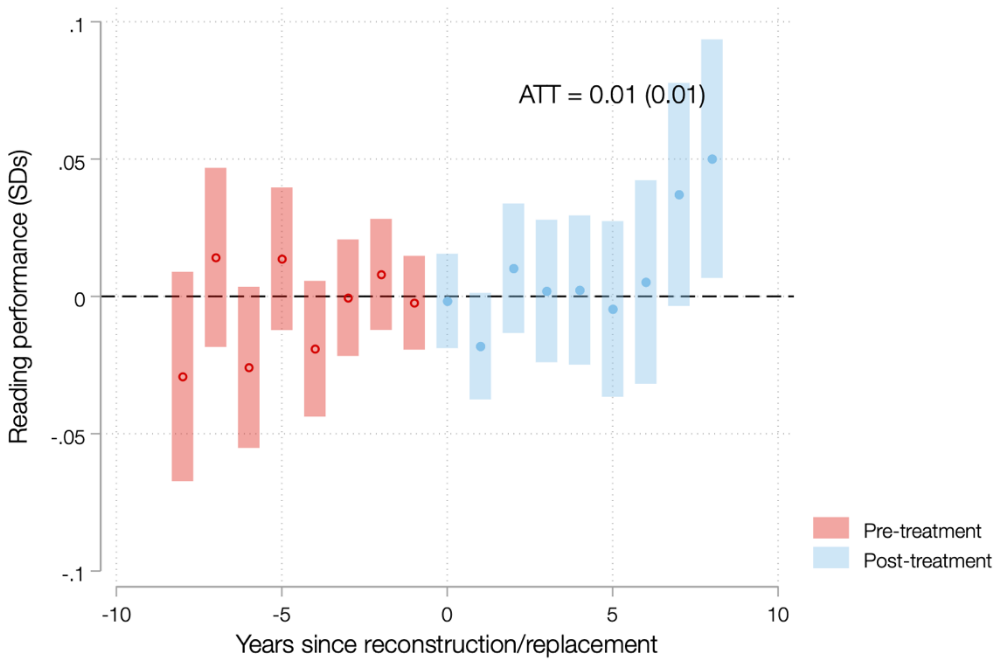
Note. All event studies above come from the Callaway and Sant'Anna (2021) doubly robust difference-in-differences estimator, with stabilized inverse probability weighting based on baseline covariates of pupil-to-teacher ratio, log enrollment, percent students free or reduced-price lunch, percent students 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.

Figure A5. Event Studies of System Reconstruction/Replacement and Student ELA Scores

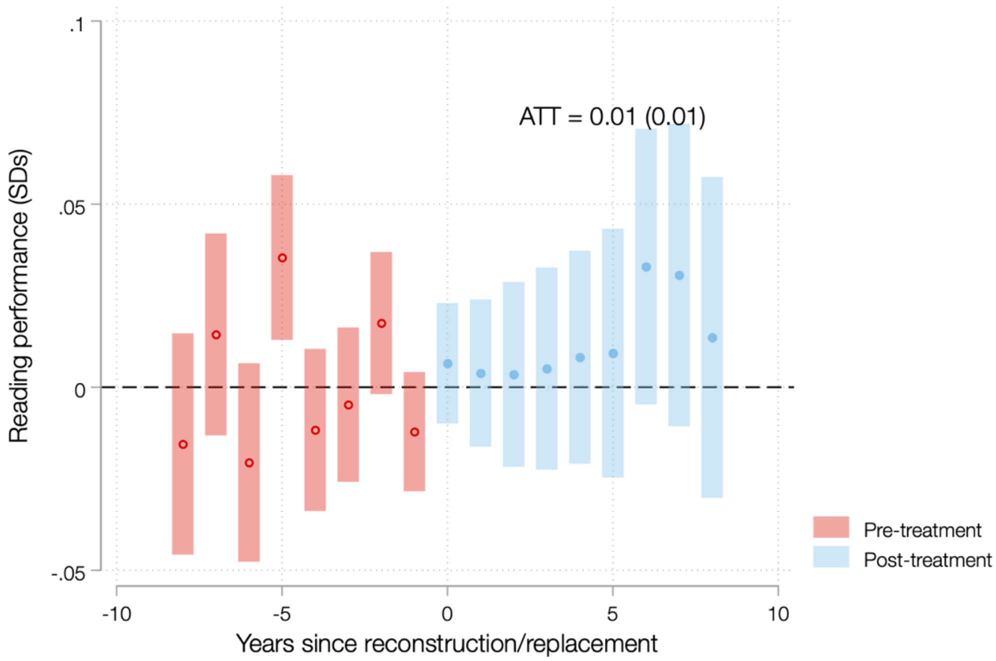
(a) Cooling System



(b) Heating System



(c) Ventilation System



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.

Table A1. Number of Schools with Major Changes in HVAC System Condition

System	Any Change in Condition	Improvement Only	Deterioration Only	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 (2,230) with the specified type of change in system.

Table A2. Effects of HVAC System Condition on Indoor Air Quality

	Air Quality Fair/Good	Air Quality Poor	Air Quality Fair	Air Quality Good
Cooling system satisfactory	0.0679**	-0.0241**	-0.0402**	0.1081**
	(0.004)	(0.003)	(0.007)	(0.007)
Heating system satisfactory	0.1032**	-0.0444**	-0.0405**	0.1437**
	(0.006)	(0.004)	(0.009)	(0.009)
Ventilation satisfactory	0.1208**	-0.0850**	-0.0631**	0.1839**
	(0.004)	(0.003)	(0.007)	(0.007)
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. 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 A3. Effects of HVAC System Condition on Student Outcomes, Controlling for Major Renovations and Construction Spending

	Absence (IRR)	Suspension (IRR)	Reading (SDs)	Math (SDs)
Cooling system satisfactory	0.9854	1.0088	0.0256*	0.0069
	(0.010)	(0.012)	(0.012)	(0.014)
Heating system satisfactory	0.9704*	0.9476**	0.0322+	0.0533**
	(0.012)	(0.014)	(0.019)	(0.019)
Ventilation satisfactory	0.9740**	0.9250**	0.0175	0.0275+
	(0.010)	(0.011)	(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	30,740	28,458	26,231	26,231
Schools	2,830	2,656	2,305	2,303

Note. Robust standard errors in parentheses, clustered by school. All models include school and year fixed effects and control variables: major renovation in past year, capital outlay for construction per pupil, pupil-to-teacher ratio, log enrollment, percent students FRL, percent students ELL, percent students Black, percent students Hispanic, percent students Asian, percent students Native American and percent students multiracial.

Table A4. Effects of HVAC System Condition on Student Outcomes in Survey Year

	Absence (IRR)	Suspension (IRR)	Reading (SDs)	Math (SDs)
Cooling system satisfactory	0.9965	1.0427*	0.0108	0.0070
	(0.016)	(0.020)	(0.017)	(0.018)
Heating system satisfactory	0.9481*	0.9545+	0.0217	0.0503*
	(0.020)	(0.023)	(0.025)	(0.025)
Ventilation satisfactory	1.0182	0.9769	0.0075	0.0091
	(0.017)	(0.018)	(0.018)	(0.019)
Estimator	Poisson	Poisson	OLS	OLS
Controls	Yes	Yes	Yes	Yes
School FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Observations	12,746	11,072	10,186	10,184
Schools	2,807	2,481	2,292	2,293

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 A5. Effects of HVAC System Condition on Student Outcomes, All Same Regression

	Absence (IRR)	Suspension (IRR)	Reading (SDs)	Math (SDs)
Cooling system satisfactory	0.9933	1.0387**	0.0216+	-0.0020
	(0.011)	(0.013)	(0.013)	(0.014)
Heating system satisfactory	0.9794	0.9732+	0.0264	0.0467*
	(0.013)	(0.016)	(0.020)	(0.020)
Ventilation satisfactory	0.9810+	0.9210**	0.0054	0.0167
	(0.011)	(0.012)	(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	12,746	11,072	10,186	10,184
Schools	2,807	2,481	2,292	2,293

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 A6. Effects of Detailed HVAC System Condition on Student Outcomes

	Absence (IRR)	Suspension (IRR)	Reading (SDs)	Math (SDs)
Cooling system unsatisfactory	Omitted	Omitted	Omitted	Omitted
Cooling system satisfactory	0.9829+	1.0169	0.0289*	0.0076
	(0.009)	(0.012)	(0.012)	(0.014)
Cooling system excellent	0.9956	0.9928	0.0306	0.0135
	(0.016)	(0.019)	(0.021)	(0.024)
Heating system unsatisfactory	Omitted	Omitted	Omitted	Omitted
Heating system satisfactory	0.9734*	0.9358**	0.0245	0.0444*
	(0.012)	(0.014)	(0.019)	(0.019)
Heating system excellent	0.9629*	0.9541**	0.0258	0.0556*
	(0.015)	(0.017)	(0.021)	(0.022)
Ventilation unsatisfactory	Omitted	Omitted	Omitted	Omitted
Ventilation satisfactory	0.9807*	0.9319**	0.0204	0.0276+
	(0.009)	(0.010)	(0.014)	(0.015)
Ventilation excellent	0.9616*	0.9282**	0.0368	0.0454+
	(0.017)	(0.019)	(0.023)	(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	33,778	31,535	28,609	28,609
Schools	2,830	2,678	2,310	2,308

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 A7. DIDM Effects of HVAC System Condition on Student Outcomes

	Absence (Percent of Days)	Suspension (Per 100 Students)	Reading (SDs)	Math (SDs)
Cooling system satisfactory	0.2034 (0.371)	-0.3644 (0.244)	0.0301 (0.019)	-0.0111 (0.022)
Heating system satisfactory	-0.1425 (0.281)	-2.7280** (0.999)	0.0102 (0.043)	0.1010* (0.050)
Ventilation satisfactory	-0.1954 (0.266)	-0.7497* (0.369)	0.0040 (0.024)	0.0709** (0.026)
Estimator	DIDM	DIDM	DIDM	DIDM
Controls	Yes	Yes	Yes	Yes
Observations	30,740	28,458	26,231	26,231
Schools	2,830	2,656	2,305	2,303

Note. This table shows findings from the Chaisemartin & D'Haultfoeuille 2024 DID dynamic estimator using average event study estimates across the first four years. Robust standard errors in parentheses, clustered by school. All models include the following 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 HVAC System Reconstructions/Replacements on Student Outcomes, Never Treated Schools as Comparison Group

	Absence (Per 100)	Suspension (Per 100)	Reading (SDs)	Math (SDs)
Cooling system replacement	0.0333	0.1389	0.0100	0.0361*
	(0.151)	(0.135)	(0.015)	(0.016)
Heating system replacement	-0.0629	-0.0882	0.0101	0.0425**
	(0.121)	(0.120)	(0.014)	(0.016)
Ventilation replacement	-0.0483	-0.0430	0.0122	0.0160
	(0.152)	(0.126)	(0.015)	(0.017)
Estimator	CSDID	CSDID	CSDID	CSDID
Controls	Yes	Yes	Yes	Yes
Observations	33,778	31,535	28,609	28,609
Schools	2,830	2,678	2,310	2,308

+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.