The Cleaner the Air, the Better They Fare: The Effects of Air Filtration on Student Achievement

Claudia Persico,
Department of Public Administration and Policy, School of Public Affairs, American University, NBER and IZA
cpersico@american.edu

Sarah Crittenden Fuller
Education Policy Initiative at Carolina, Department of Public Policy, University of North Carolina at Chapel Hill
sarah.fuller@unc.edu

February 2025

Abstract

There is mounting evidence that exposure to contemporaneous air pollution makes people more likely to engage in risky behavior and make mistakes more generally, as well as affecting test scores for students in school. However, there is little evidence for the effectiveness of interventions to address this issue. Using detailed data on all students in North Carolina public schools matched with data on air purification upgrades and ESSER funding, we estimate the effects of air purification upgrades in schools on student achievement. We find that installing air purification systems led to improvements in test scores and grades, and a reduction in absences and chronic absenteeism.

JEL: Q52, Q53, I14

* This research was conducted with restricted access to North Carolina education data. We are grateful to the generous funding and support provided by the American Institutes for Research (AIR). We are also grateful to participants at the AEFP conference. We thank Camille Mikkelson for cleaning the HVAC spending data.

I. Introduction

Recent studies have found that over one fifth (21.8 percent) of U.S. schools are within one mile of an industrial polluting (Toxic Release Inventory) site (Persico and Venator 2019) and over 6.4 million children attend public school within 250 meters of a major roadway (Kingsley et al. 2014), suggesting that large number of children are exposed to air pollution in school. There is mounting evidence that exposure to contemporaneous air pollution affects student achievement and behavior (Persico and Venator 2019; Heissel, Persico and Simon 2021).

Because housing is generally cheaper near sources of pollution, this has troubling implications for the intergenerational persistence of poverty as it suggests a link between pollution exposure and individuals' economic outcomes (Persico 2022). Black, Hispanic and low-income children are more likely to experience higher air pollution, suggesting a major source of inequality (Currie et al 2023). It also suggests that we are squandering potential by failing to fully develop our youths' human capital. Indeed, sustained exposure to pollution harms numerous educational outcomes (Persico and Venator 2019) and air quality on the day of standardized testing lowers test scores (Ebenstein et al. 2016; Marcotte 2017). Even within zip codes, microclimates can contribute to inequality and hinder human capital accumulation, as students who move to a school that's downwind of a highway experience more traffic pollution, which harms achievement and increases suspensions and absences (Heissel, Persico, & Simon 2019).

While a growing literature is focused on the effects of exposure to pollution on children, there is little evidence for how to address air quality in schools on a budget. We use rich individual-level data on students in schools across the state of North Carolina matched with data

on the timing of upgrades to air filtration systems in schools from Elementary and Secondary School Emergency Relief (ESSER) funding and information we gathered from districts.

Using data on the timing of when schools upgraded their HVAC systems and the formula through which the ESSER funds were allocated, we use a student and school fixed effects design to estimate the effectiveness of air purification systems on test scores, student absences, chronic absenteeism, and grades. In other words, we compare students within schools before versus after the schools upgrade their air filtration systems, compared to comparison schools that did not upgrade their air filtration systems during the same time period, controlling for the formula characteristics by which the ESSER funding was allocated (namely, district poverty levels that determine Title I funding).

We find that air purification upgrades improve test scores by 3.3% of a standard deviation and grades by 10% of a grade. We also find that HVAC upgrades reduce absence rates by 0.2 percentage points and reduce chronic absenteeism by 0.8 percentage points. Our preferred specification includes student, school, grade and year fixed effects, where the treatment is a binary variable for a particular school having updated the air purification system in that year. We include student fixed effects to hold constant any time invariant characteristics of students and to account for potential selection into or out of schools. We also estimate models with school-grade and grade-year fixed effects to account for any other common shocks students or schools might experience during our time window.

Our results suggest that HVAC and other air purification upgrades in schools provide strong benefits to students in terms of improving achievement and reducing absences, even in the current climate. This suggests that air quality issues can be mitigated by schools to protect student health and learning.

II. Background

A. Evidence on Pollution and Academic Outcomes

The COVID-19 pandemic has changed the way we understand building ventilation and its importance in keeping us safe from viruses and bacteria in the air. There is evidence that school ventilation protects children from contracting COVID-19 and other viruses in schools (Prather et al 2020; EMG 2020). Research suggests that COVID-19 spreads in schools in situations where there are high case rates in the surrounding community, and children can still catch COVID-19 in school buildings that are not properly ventilated (Goldhaber et al 2020; Harris, Ziedan and Hassig 2021).

Persico and Johnson (2021) also show that higher air pollution can make people more likely to get sick with and die from COVID-19. Because air pollution harms the immune system, it can increase the likelihood of infection from airborne diseases. It also can exacerbate existing cases of COVID-19 by harming the immune systems of infected people. They used the variation in pollution caused by a rollback of environmental enforcement during the pandemic to estimate the effects of increased pollution on county-level COVID-19 deaths and cases. They find that counties with more Toxic Release Inventory (TRI) sites saw an 11.8% increase in air pollution on average following the EPA's rollback of enforcement, compared to counties with fewer TRI sites. They also find that these policy-induced increases in air pollution are associated with a 53% increase in cases and a 10.6% increase in deaths from COVID-19.

In addition, a variety of causal papers have examined how pollution in particular affects human capital outcomes, like educational attainment, health, mortality, and wages, even at levels below current regulatory standards (Graff Zivin and Neidell 2013). Some recent studies find that contemporaneous school bus pollution affects students' test scores and respiratory health

(Austin, Heutel and Kreisman 2019; Beatty and Shimshack 2011). Retrofitting 10% of school bus engines to be cleaner increased English test scores by 0.009 standard deviations. Currie et al (2009) finds that days of high carbon monoxide increase absences from school. Marcotte (2017) also finds that students score 1 to 2 percent lower on math and reading scores on days of high particulate matter and pollen on the day of the exam.

Persico and Venator explore what happens when a Toxic Release Inventory site opens or closes near a school. They find that exposure to pollutants in schools has significant, negative impacts on test scores and being suspended or absent from school. They also find that a TRI site opening within one mile of a school is associated with lower performance on school accountability measures, meaning that there is an increase in the likelihood that a school's ranking on these measures drops one or more levels.

Over 6.4 million U.S. children attend public school within 250 meters (about the length of three American football fields) of a major roadway. Heissel, Persico and Simon (2019) investigate pollution exposure of students who graduate from elementary to middle school or from middle school to high school. They compare children who switch from a school that is upwind from a highway to a school that is downwind of a highway, and find that attending a school downwind of a highway is associated with 0.04 of a standard deviation lower test scores, a 4 percentage point increase in behavioral incidents, and a 0.53 percentage point increase in the rate of absences over the school year. Children who attend school near a major highway are again more likely to be low income or minority than children attending school elsewhere.

The pandemic has also brought into sharp relief the disparities that exist between school building quality in richer and poorer neighborhoods. According to the Government Accountability Office's national survey of school districts (U.S. GAO 2020), about 54% of

public-school districts need to update or replace multiple building systems or features in their schools. They estimate that about 36,000 schools need HVAC updates, and 41% need to update or replace heating, ventilation or air conditioning. They also find that capital construction expenditures were on average $300 less per student in high poverty districts ($719 per student), compared to low poverty districts ($1,016 per student). This funding disparity reflects fewer resources to spend despite the greater needs of lower income districts in most cases. Whereas wealthier districts make up state funding shortfalls through raising local taxes, high-poverty districts are more likely to rely on state funding and have difficulty making up the difference in lean years.

So how much might HVAC system upgrades in schools help? In a recent study, Gilraine finds that putting air purifiers in classrooms led to a 0.2 standard deviation increase in test scores for children, compared to children in local schools that did not get the air purifiers (Gilraine 2020). This is similar to the effect of small class sizes in the famous Tennessee Project STAR experiment. He estimates that the annual cost of installing air purifiers throughout a school is $1,000. Similarly, Stafford (2015) finds that indoor air quality renovations at schools in Texas improved test scores by 0.15 standard deviations. This suggests that air filtration, like that offered by modern HVAC systems, could improve children's academic and behavioral outcomes long after the COVID-19 pandemic has concluded. Low-income children stand to be impacted the most by improvements in air quality, since there is evidence that their school buildings are in worse shape in many places and they are more likely to live near sources of pollution (Persico, Figlio and Roth 2020).

B. ESSER Funding

The COVID-19 pandemic created a unique financial opportunity for states and districts as policymakers across the nation responded to the crisis by allocating emergency relief funds to support schools and communities in mitigating and recovering from the educational harms of the pandemic. The largest of these relief funds was the Elementary and Secondary School Emergency Relief (ESSER) Funds, which allocated nearly $190 billion in funding to K-12 schools nationwide. ESSER funding could be used by schools and districts to directly address health concerns created by the pandemic, to support students and educators during school closures, and to address the impacts of the pandemic on students and educators. States and districts were given a great deal of flexibility in how they utilized these funds with 90 percent of funding flowing to districts for local decision making.

ESSER funds were allocated to states and to districts within states in proportion to existing Title I allocations which are driven primarily by the Formula Eligible Population (FEP) (primarily children below the poverty line) within each district (Gordon & Reber, 2022; Goldhaber & Falken, 2024). This allocation process was intended to provide more funding for lower income districts, which may have higher needs, and resulted in substantial variation in the amount of funding per pupil received by individual districts. In North Carolina, low poverty districts received an average of $3,147 ESSER funds per pupil while high poverty districts received an average of $7,796 per pupil (Mikkelsen et al., 2023). These large differences in the size of allocations may contribute to differences in allocation decisions across districts with different characteristics.

Research shows that, among other spending areas, pandemic recovery funds have been used by states and districts across the nation to support staffing, academic recovery, and facilities and operations efforts. Broken down into more granular categories, states and districts have

elected to spend most of their money on salaries for teachers and interventionists, HVAC improvements and replacements, summer learning and afterschool academic support, repairs to facilities to prevent illness, and staff retention and recruitment (DiMarco & Jordan, 2022; Brooks & Springer, 2024). Spending plans and actual expenditures in NC follow similar patterns. Analyses of district spending plans in NC show districts prioritized spending on staffing, facilities and operations, and academic interventions with the common stated goals of academic recovery, improving air quality, and providing summer learning opportunities (Mikkelsen, Fuller, & Black, 2023; Manuel & Mikkelsen, 2023).

The widespread investments in improving air quality supported by ESSER funds represent a unique one-time investment in improving environmental health in school buildings. In North Carolina, HVAC replacements and repairs were the most common facilities investment, and the most common investment related to air quality included in district ESSER spending plans (Mikkelsen et al., 2023; Manuel & Mikkelsen, 2023). Nationwide, high poverty districts, in particular, have disproportionately spent ESSER dollars on HVAC and improving air quality compared to salaries for teachers and counselors or running summer learning programs (Jordan & DiMarco, 2022b; Brooks & Springer, 2024). Similarly, in North Carolina, 90 percent of high poverty districts planned to invest in HVAC repair or replacement compared to just 57 percent of low poverty districts (Mikkelsen et al., 2023).

Researchers have begun to estimate the impact of the overall ESSER investments on student outcomes. In particular, two studies use the variation in ESSER allocations created by the Title I funding formula and the lag in data used to calculate district poverty rates to estimate the impact of ESSER funding. Goldhaber (2024) finds that each $1,000 increase in ESSER per pupil funds led to statistically significant increases in district math scores of 0.008 standard deviations

and similar but statistically insignificant increases in ELA scores in a study using data from 30 states. Similarly, Dewey and colleagues (2024) found that ESSER investments significantly increased both math and reading test scores of students. These overall estimates suggest that the resources provided to students and schools through ESSER funding assisted in pandemic recovery but don't distinguish *which* investments yielded positive benefits for students. Many studies are underway looking at the impacts of academic interventions and additional staffing paid for through ESSER funding, but, to our knowledge, this study is the first to look at whether the HVAC investments made by many districts resulted in improvements in student outcomes.

III. Data.

A. Student-level data

We use rich, population-level data on every child attending public school in North Carolina from 2020 to 2023. Because the COVID-19 pandemic caused massive changes in how schools functioned, from virtual learning and test score losses to large increases in student absences, we focus on the period of the pandemic to the present. This includes approximately 1,500,000 students across 2,500 schools in each year. These data link individual-level education outcomes to classrooms within schools and schools within districts. The data also include detailed information on student demographic characteristics, such as race and socioeconomic status, the schools and classrooms children attended, test scores, absences, grades, as well as teacher characteristics.

In this study, we focus on three sets of student outcomes – standardized test scores, absences, and grades. For test score measures, we use End-of-Grade (EOG) math and reading tests taken in grades 3 through 8 each year. These test scores are standardized to have a mean of zero and a standard deviation of 1 within year, grade, and subject. For some specifications, test scores are

reported separately by subject, otherwise they are averaged within student across subject. We measure student absences in two ways. First, we use a continuous measure of percent of days absent which is calculated by dividing the numbers of days absent by the number of days in membership for each student.[1] We also create an indicator for whether a student was chronically absent, defined as missing 10 percent or more of school days in membership. Absence measures are available for all grade levels. We represent student grades as mean quality points averaged across all courses with grades for an individual student in a given year, where an A is equal to 4 points, a B is equal to 3 points, a C is equal to 2 points, a D is equal to 1 point, and an F is equal to zero points. Mean quality points can be calculated for students in grades 6 through 12. All of these outcome measures are repeated measures which can be measured across years for individual students.

B. ESSER Data and Other Data on HVAC System Upgrades

We match our individual-level data following children though school to data on when each school fixed or updated its HVAC system using two additional sources of data: (1) the Public School Building Capital Fund - Monthly Projects Report and (2) expenditure data for ESSER funding. While most HVAC upgrades during this time were likely funded by the recent Elementary and Secondary School Emergency Relief (ESSER) funds, some schools used the lottery fund to upgrade their HVAC systems. We identified these schools using the Public School Building Capital Fund Monthly Projects report, which lists all HVAC replacements and upgrades in each month.

[1] We use percent of days absent rather than a raw measure of days absent to account for small differences in the number of days of school across years and across school districts as well as to allow for the inclusion of students who switch schools during the school year.

We used object codes in the ESSER expenditure data obtained from North Carolina's Department of Public Instruction to identify HVAC-related repairs and upgrades funded by district level ESSER funds and the schools for which these funds were expended. We verified these data through interviews with school district officials, examining ESSER spending data, and collecting news stories about upgrades. HVACs are relatively expensive investments, so we classified a school as having an HVAC upgrade if they spend more than $200,000 at the school level on HVAC related codes.[2] Between 2020 and 2023, we identified 530 schools with updates to their HVAC systems. We focus on HVAC upgrades that occurred during this time period because ESSER spending plans and conversations with districts indicate that upgrades during this time period include advanced filtration intended to improve air quality, whereas earlier upgrades may or may not include air filtration. However, there is some possibility that we are missing some schools that upgraded their HVAC systems, which would bias our results towards zero.

C. Pollution Data

We also use data from the Environmental Protection Agency (EPA) that includes daily data on the Air Quality Index, which is a scale between 0 and 500 indicating the amount of pollution in the air. Higher scores indicate more air pollution. The AQI is predominantly determined by Particulate Matter 2.5 (PM2.5), also known as fine particulate matter, and ozone. In addition, we have daily data from pollution monitors on the amounts of PM2.5, Particulate Matter 10 (PM10), ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide and lead in the air, as measured by the EPA's pollution monitors. The pollution monitors include information on latitudinal and longitudinal coordinates, and the Public School Universe Survey from the

[2] The average planned spending on HVACs per school nationwide was $267,180 (Sauter and Heming 2022).

National Center for Education Statistics also has data on the latitudinal and longitudinal coordinates of each school in the United States. This allows us to link each school with the nearest pollution monitor. We use inverse distance weighting of the distance between each school and pollution monitor to adjust for the fact that some schools will have closer pollution monitors than others. Together, these pollution monitor data allow us to determine which schools are in more polluted areas in North Carolina.

IV. Empirical Strategy

Using these data on the timing of when schools upgraded their HVAC systems, we use a student and school fixed effects design to estimate the effectiveness of air purification systems on test scores, grades, student absences and chronic absenteeism. In other words, we compare students within schools before versus after the schools upgrade their air filtration systems, compared to comparison schools that did not upgrade their air filtration systems during the same time period. Because the ESSER funding was allocated via Title I funding, we control for the percentage of a district in poverty (i.e. the FEP) in the year for which the ESSER funding was allocated in order to control for selection into treatment that was driven by the size of ESSER allocations received by the district.

We estimate models with student, school, grade and year fixed effects, where the treatment is a binary variable for a particular school having updated the air purification system in that year, as follows:

$$(1)\quad Y_{isgt} = \beta_1 \mathbb{1}(HVAC\ Upgraded)_{st} + \beta_2 X_{it} + \beta_3 Z_{dt} + \alpha_i + \gamma_s + \delta_g + \theta_t + \epsilon_{iszt}$$

Y_{isgt} represents a student-level outcome, such as test scores, grades, absences, or chronic absenteeism. The indicator $\mathbb{1}(HVAC\ Upgraded)_{st}$ is equal to one if a school upgraded its HVAC system in that year, and it remains one in the following years. Otherwise, it is zero. Our

parameter of interest is therefore β_1, which represents the effect on an outcome from an HVAC upgrade. X_{it} is a vector of observable time-varying individual characteristics, including economically disadvantaged status, and Z_{dt} is a vector of observable time-varying district-level characteristics, including the log of non-HVAC related ESSER expenditures in that year, the percentage of students who are economically disadvantaged in the district, the racial composition of the district, and lagged FEP. Since ESSER funding was allocated at the district level on the basis of lagged FEP, these are important controls to address potential selection into treatment. We also control for school fixed effects (γ_s), student fixed effects (α_i), grade fixed effects (δ_g), and year fixed effects (θ_t). By including student fixed effects, we hold constant any time invariant characteristics of students, such as the amount of virtual learning a student received during the pandemic, and account for potential selection into or out of schools.

Table 1 shows descriptive statistics for the number of schools who upgraded their HVAC systems with air purification upgrades between 2020-2023, school characteristics, as well as the average PM2.5 (fine particulate matter) over time. There are some important differences between schools that decided to upgrade their air purification (HVAC) systems and schools that did not. For example, HVAC upgrades were more likely in larger districts and larger schools with higher ESSER expenditures and more teachers with a Masters degree. These districts also had slightly higher shares of Black and Hispanic students, as well as Limited English Proficiency (LEP) students. Children attending these schools also experienced slightly higher pollution on average than children attending schools that did not upgrade their HVAC systems.

Panel A of Figure 1 also shows the cumulative number of children experiencing an HVAC improvement over time, while Panel B of Figure 1 shows the number of schools with air purification upgrades in each year. 530 schools upgraded their HVAC systems over this time

period, affecting 447,926 students. The comparison group is the 2,023,791 students attending a school that did not upgrade their HVAC systems from 2020-2023.

V. Results

Our main results are presented in Panel A of Table 2. We find that upgrading HVAC systems during the pandemic increased test scores in both Math and Reading by 3.1% and 2.1% of a standard deviation respectively, and 3.3% of a standard deviation overall. Column 6 also shows that HVAC upgrades increased grades by about 0.1 quality points, or about 10% of a letter grade. Given that we control for non-HVAC ESSER-related spending at the district level each year to address other potential interventions and spending that might affect student outcomes in each year, we can compare the effects of HVAC upgrades versus all other non-HVAC expenditures. We find that $1000 more per pupil expenditures on non-HVAC related things was associated with a 0.6% of a standard deviation improvement in math scores and a 0.8% of a standard deviation improvement in standardized test scores overall. This is similar to what Goldhaber and Falken (2024) find, albeit somewhat smaller in magnitude. This suggests that some of the improved outcomes are driven through cleaner air from HVAC upgrades. However, the spending is not associated with improvements in grades, absence rates or chronic absences.

We also find that HVAC upgrades were associated with a 0.2 percentage point reduction in days absent. This represents a 2.7% reduction in absences relative to the mean. Given that there are 180 days in the school year in North Carolina, this is a reduction in 0.36 days absent over the year. We also see a reduction in chronic absenteeism of 0.8 percentage points, or a 3.7% reduction in chronic absences. During and following the pandemic, chronic absences have increased dramatically, and upgrading HVACs is one of the few interventions that is effective in lowering chronic absences, as well as raising test scores.

The results of our event study is shown in Figure 2. We again control for student and district level demographics and student, school, grade and year fixed effects. The results are similarly positive for test scores. An important caveat is that we are only able to estimate the effects of HVAC upgrades in 2022 in this event study, since there were no test scores from 2020 and no test scores available after 2023.

When considering the size of gains from HVAC upgrades, it is important to consider that when improving air quality in a school, all students attending that school are treated. This is often not the case with other types of interventions, such as tutoring or after school programs, which may only serve a small fraction of the students at a given school. It is also important to note that the test score gains from installing and upgraded HVAC are in line with the literature on the detrimental effects of indoor air pollution on academic outcomes. For example, the effects of gaining access to an HVAC upgrade on test scores and absences are similar to the magnitude of the losses from attending a school downwind of a highway in reverse (Heissel, Persico and Simon 2021). This suggests that HVAC air purification upgrades improve outcomes nearly as much as being downwind of a highway harms outcomes.

In Panel B of Table 2, we estimate the effects of HVAC upgrades on student achievement and behavior using a school-grade, grade-year fixed effects model instead of a student, school, grade and year fixed effects model. The school-by-grade fixed effects control for unobservable characteristics of students who attend the same school and grade. Using grade-year fixed effects accounts for common shocks that might affect a particular cohort of students. The results are nearly identical to our main results in Panel A, though the effects on chronic absences are not statistically significant at conventional levels. This suggests that common shocks and unobserved characteristics of students do not drive our results.

In Panel C of Table 2, we estimate the effects of HVAC upgrades controlling for the within-student test score change between 2019 to 2021. This is meant to rule out effects that are driven by large test score losses and then reversion to the mean. We find that the results on test scores are broadly similar to our main results in Panel A when we control for test score changes before versus after the pandemic. However, the reduction in days absent, chronic absences and grades become even larger.

VI. Heterogeneity

Next, we estimate the results by a variety of different subgroups to see whether different groups are affected differently. In Table 3, we present the results by age of the students. Panel A presents results for students in grades 3-5 and Panel B presents results for students in grades 6-10. We find that students in older grades have even larger test score gains from getting an HVAC upgrade (4.2% of a standard deviation) than students in younger grades (3.2% of a standard deviation). However, nearly all of the reduction in absences from HVAC upgrades is experienced by third through fifth graders. This might be because younger children are more likely to be out of school due to illness, whereas older children might be missing school for a larger variety of reasons.

Table 4 presents the results by different demographic subgroups. Panels A and B present the results by gender and suggest that while both genders benefit from cleaner air, boys benefit slightly more than girls in terms of reduced absences and improved test scores. Panels C and D present the results by economic disadvantage. Both wealthier and lower income students see improved test scores and grades after a HVAC upgrade. However, students who are never listed as economically disadvantaged benefit more from HVAC upgrades than students who are always

listed as economically disadvantaged in terms of the magnitude of the increase in test scores and grades, as well as a reduction in absences.

Panels E, F and G show the results by race. Students from all racial groups experienced improved test scores following an HVAC upgrade. However, White and Black students experience a reduction in absences and improvement in grades after an HVAC upgrade that is not seen for Hispanic students. This might be because Hispanic students are more likely to live near sources of pollution at home that could have countervailing impacts on performance in school.

Finally, Table 5 shows the effects of HVAC upgrades on outcomes in districts that experience higher versus lower levels of pollution. Districts that experience higher than median air pollution levels show the largest benefits from HVAC upgrades, suggesting that HVACs are improving outcomes through reduced exposure to air pollution. The test score effects for students in higher than median air pollution districts are 48% larger than the test score effects for students in lower than median air pollution districts. In addition, the effect on the rate of absences, being chronically absent and grades is driven by students in higher air pollution districts. This implies that HVAC upgrades will be most effective in more polluted neighborhoods.

VII. Additional Threats to Internal Validity

To test the robustness of our results, we run a series of analyses to address the possibility of bias due to teacher or student sorting across schools. During the pandemic, air purification upgrades were very popular among teachers and parents who were concerned about getting COVID-19. If there were unobserved air purifiers in classrooms, this should bias our results towards zero. Nevertheless, there could have been teacher or student sorting in response to air purification upgrades. We test for this directly in results, presented in Table 6. We find some

mixed evidence of teacher sorting in response to HVAC upgrades. If an HVAC was upgraded, a teacher was 1.6 percentage points less likely to return to the school in the following year and 0.5 percentage point less like to teach in NC public schools. This might be because the pandemic caused a large increase in teacher turnover generally. HVAC upgrades might also have been compensatory responses in places where COVID rates were highest. Nevertheless, teacher turnover is not likely to drive improvements in outcomes for students.

We also see a small increase in teacher age and experience, though the increase in experience is not statistically significant. This suggests that the teachers who stayed were more experienced. We also see a 0.7 percentage point increase in the likelihood that a student changed schools after an HVAC system was upgraded. However, this represents a relatively small increase overall.

To further test whether students who are exposed to HVAC upgrades are more likely to have differential exposure to schools with different types of peers, we also estimate our primary specification with student, school, grade and year fixed effects where the outcomes are characteristics at the school level, presented in Panel A of Table 7. We find that students who attend schools that upgraded their HVACs see small reductions in being economically disadvantaged in that year. In addition, upgrading an HVAC is associated with a decrease in non-HVAC expenditures, which is to be expected if ESSER funding is limited. In addition, schools that got HVAC upgrades saw increases in the percentage of students who were low income in the district overall. This is likely because lower income districts were more likely to get ESSER funding, and the pandemic hit lower income places harder, resulting in even more poverty. Even with the large increase in district level poverty corresponding to the timing of HVAC

interventions, we find improvements in test scores and decreases in absences. We also find small reductions in the proportion of the district that were Black or Hispanic.

Since the ESSER funding was allocated by districts to schools, one might worry that there is selection into treatment. For example, schools that had the largest test score losses might be targeted for HVAC upgrades. In Panel B of Table 7, we show that the magnitude of a school's pandemic test score loss from 2019-2021 does not predict getting an HVAC upgrade. In this specification, the only controls are for gender and student and district demographics, along with district, grade and year fixed effects. The point estimate of zero suggests that districts were not allocating HVAC upgrades on the basis of test score changes. This again suggests that HVAC upgrades improved test scores overall, and that this was not simply a regression to the mean.

VIII. Conclusion

This is the first study to investigate the effects of HVAC upgrades during the pandemic on student achievement and behavior. Using a student fixed effects design, we find that HVAC upgrades were associated with 3.3% of a standard deviation higher test scores, a 2.7% reduction in absences, a 3.7% reduction in chronic absences, and an increase in grades of 10% of a letter grade. Given the relatively modest effects on absences, our analyses suggest that the results are being driven through reductions in pollution exposure rather than increased time in school.

The magnitudes of these effects on test scores are important, especially given how widespread student pollution exposure is in the United States. For example, Chetty, Friedman and Rockoff (2014) find that a one standard deviation improvement in teacher quality increased test scores by 0.1 standard deviations. This suggests HVAC upgrades increase test scores as much as increasing teacher quality by 0.33 standard deviations would. Given that the average amount spent on HVAC upgrades was $267,180 (Sauter and Heming 2022) and the average

school size for schools who upgraded their HVACs is 1,116, this implies spending $239.41 per student on HVACs with a test score improvement of 3.3% of a standard deviation. Spending $239.41 on non-HVAC related things would be associated with only a 0.14% of a standard deviation improvement in test scores. Compared with the non-HVAC per pupil expenditures, HVAC related expenditures are strikingly effective. In addition, air quality improvements reduce absences and chronic absences and improve grades.

We find strong evidence of HVAC upgrades improving test scores, grades and absences, even though parents and teachers might practice avoidance behaviors in classrooms and at home to limit children's exposure to pollution. For example, if parents were bringing air purifiers into classrooms, this would bias our findings towards zero. Taken together, this suggests that these estimates are lower bounds on the true effect of HVAC upgrades on children's health and cognitive development.

In addition, while research has shown that pollution negatively impacts test scores and student absences, there are few studies that suggest a solution to this problem. Finally, of the studies that exist, ours is the only one to our knowledge that examines the effects of air purification upgrades during and after the pandemic. This is important for understanding how beneficial these upgrades might be in today's schools and suggests some lessons for policy. First, the HVAC upgrades are most effective in districts with higher levels of pollution. Second, our study suggests that much of the benefit of ESSER funding in North Carolina was due to HVAC upgrades, as opposed to other spending.

Finally, students across demographic categories saw achievement improvements following HVAC upgrades, suggesting that this intervention benefits all children, as opposed to other programs that require take up (such as after school tutoring). This is important, considering

that Black, Hispanic and low-income children are more likely to be exposed to higher levels of air pollution, causing inequality in outcomes. Improving indoor air quality though HVAC upgrades in schools is one of the few policies that can be used to address this type of environmental inequality.

References

Austin, Wes, Garth Heutel, and Daniel Kreisman. "School Bus Emissions, Student Health and Academic Performance." *Economics of Education Review* 70 (June 1, 2019): 109–26. https://doi.org/10.1016/j.econedurev.2019.03.002.

Beatty, Timothy K. M., and Jay P. Shimshack. "School Buses, Diesel Emissions, and Respiratory Health." *Journal of Health Economics* 30, no. 5 (September 1, 2011): 987–99. https://doi.org/10.1016/j.jhealeco.2011.05.017.

Currie, Janet, John Voorheis, and Reed Walker. "What Caused Racial Disparities in Particulate Exposure to Fall? New Evidence from the Clean Air Act and Satellite-Based Measures of Air Quality." *American Economic Review* 113, no. 1 (January 2023): 71–97. https://doi.org/10.1257/aer.20191957.

Chetty, Raj, John N. Friedman, and Jonah E. Rockoff. 2014. "The Long-Term Impacts of Teachers II: Teacher Value-Added and Student Outcomes in Adulthood." American Economic Review 104 (9): 2633–79. https://doi.org/10.1257/aer.104.9.2633.

Dewey, Dan C., Erin M. Fahle, Thomas J. Kane, Sean F. Reardon, and Douglas O. Staiger. "Federal Pandemic Relief and Academic Recovery." Working Paper. Working Paper Series. National Bureau of Economic Research, September 2024. https://doi.org/10.3386/w32897

Ebenstein, Avraham, Victor Lavy, and Sefi Roth. "The Long-Run Economic Consequences of High-Stakes Examinations: Evidence from Transitory Variation in Pollution." *American Economic Journal: Applied Economics* 8, no. 4 (October 2016): 36–65. https://doi.org/10.1257/app.20150213.

Gilraine, Michael. "Air Filters, Pollution, and Student Achievement." *Journal of Human Resources*, February 7, 2023, 0421. https://doi.org/10.3368/jhr.0421-11642R2.

Goldhaber, Dan, Scott A. Imberman, Katharine O. Strunk, Bryant Hopkins, Nate Brown, Erica Harbatkin, and Tara Kilbride. "To What Extent Does In-Person Schooling Contribute to the Spread of COVID-19? Evidence from Michigan and Washington." National Bureau of Economic Research, February 15, 2021. https://doi.org/10.3386/w28455.

Goldhaber, Dan and Grace Falken (2024). ESSER and Student Achievement: Assessing the Impacts of the Largest One-Time Federal Investment in K12 Schools. CALDER Working Paper No. 301-0624

Gordon, Nora, and Sarah Reber. "Federal Aid to School Districts during the Covid-19 Recession." *National Tax Journal* 73, no. 3 (September 1, 2020): 781–804. https://doi.org/10.17310/ntj.2020.3.07.

GOV.UK. "EMG: Role of Ventilation in Controlling SARS-CoV-2 Transmission, 30 September 2020." Accessed May 17, 2021. https://www.gov.uk/government/publications/emg-role-of-ventilation-in-controlling-sars-cov-2-transmission-30-september-2020.

Graff Zivin, Joshua, and Matthew Neidell. "The Impact of Pollution on Worker Productivity." *American Economic Review* 102, no. 7 (December 2012): 3652–73.

Heissel, Jennifer A., Claudia Persico, and David Simon. "Does Pollution Drive Achievement? The Effect of Traffic Pollution on Academic Performance." *Journal of Human Resources,* April 9, 2020, 1218-9903R2. https://doi.org/10.3368/jhr.57.3.1218-9903R2.

Kingsley, Samantha L., Melissa Eliot, Lynn Carlson, Jennifer Finn, David L. MacIntosh, Helen H. Suh, and Gregory A. Wellenius. "Proximity of US Schools to Major Roadways: A Nationwide Assessment." *Journal of Exposure Science & Environmental Epidemiology* 24, no. 3 (2014): 253–59. https://doi.org/10.1038/jes.2014.5.

Manuel, Erin W., and Camille N. Mikkelsen. (2023). ESSER III Investments in North Carolina: A Preliminary Analysis of PRC 181 and PRC 182. (EdWorkingPaper: 23-762). Retrieved from Annenberg Institute at Brown University: https://doi.org/10.26300/rpq3-y632

Marcotte, Dave E. "Something in the Air? Air Quality and Children's Educational Outcomes." *Economics of Education Review* 56 (February 1, 2017): 141–51. https://doi.org/10.1016/j.econedurev.2016.12.003.

Mikkelsen, Camille N., Sarah C. Fuller and Delaney Black. *In for a Dollar: A Descriptive Look at How North Carolina Traditional School Districts Have Planned and Used COVID-19 Emergency Funding*. Education Policy Initiative at Carolina. Chapel Hill, NC. (June 2023). https://epic.unc.edu/wp-content/uploads/sites/1268/2023/07/In-For-a-Dollar-Research-Brief-Final.pdf

Persico, Claudia. "Can Pollution Cause Poverty? The Effects of Pollution on Educational, Health and Economic Outcomes." Working Paper. Working Paper Series. National Bureau of Economic Research, October 2022. https://doi.org/10.3386/w30559.

Persico, Claudia, David Figlio, and Jeffrey Roth. "The Developmental Consequences of Superfund Sites." *Journal of Labor Economics,* October 9, 2019. https://doi.org/10.1086/706807.

Persico, Claudia L., and Kathryn R. Johnson. “The Effects of Increased Pollution on COVID-19 Cases and Deaths.” *Journal of Environmental Economics and Management* 107 (May 1, 2021): 102431. https://doi.org/10.1016/j.jeem.2021.102431.

Persico, Claudia L., and Joanna Venator. “The Effects of Local Industrial Pollution on Students and Schools.” *Journal of Human Resources*, August 6, 2019, 0518.

Prather, Kimberly A., Linsey C. Marr, Robert T. Schooley, Melissa A. McDiarmid, Mary E. Wilson, and Donald K. Milton. “Airborne Transmission of SARS-CoV-2.” *Science* 370, no. 6514 (October 16, 2020): 303–4. https://doi.org/10.1126/science.abf0521.

Sauter, Neil and Heming, Anisa. “School Facilities Funding in the Pandemic: An Analysis of Planned Facilities Spending under ARP-ESSER Funding.” Center for Green Schools at the U.S. Green Building Council. (November 2022).

Tables.

Table 1: Characteristics of Children and Schools

Sample:	(1) All children attending public school in North Carolina	(2) Children who Attend School with an Air Purification Upgrade	(3) Children who do not Attend School with an Air Purification Upgrade
Average test score	0.019	0.165	-0.007
Pct Days Absent	7.4%	8.2%	7.3%
School Size	870	1,116	834
District Size	48,950	94,197	45,777
Average HVAC Expenditures (District)	$3,089,948	$7,891,239	$1,558,237
Average Non-HVAC Expenditures (District)	$30,268,782	$86,686,822	$22,079,339
Average PM2.5 (in $\mu g/m^3$)	8.04	8.25	8.01
Limited English Proficiency	8.6%	10.3%	8.4%
Share of teachers with an MA degree	35.4%	42.0%	34.7%
Share economically disadvantaged	42.5%	38.6%	43.1%
Lagged Poverty Rate (for Title I Funding)	19.9%	14.0%	20.7%
Share Black	24.9%	25.1%	24.9%
Share Hispanic	19.8%	20.6%	19.7%
N Students	6,258,919	793,361	5,465,558

Notes: This table shows descriptive statistics for all students in NC schools from 2020 to 2023 in Column 1, students in schools with HVAC upgrades in Column 2, and students in schools without HVAC upgrades in Column 3.

Table 2: The Effects of Air Purification on Outcomes

	(1) Math Scores	(2) Reading Scores	(3) Test Scores	(4) Pct Days Absent	(5) Chronically Absent	(6) Grades
	Panel A: Full Sample (with Student, School, Year, and Grade FEs)					
HVAC Upgraded	0.031***	0.021***	0.033***	-0.0022***	-0.008***	0.100***
	(0.003)	(0.003)	(0.002)	(0.000)	(0.001)	(0.003)
Non-HVAC Per Pupil Expenditures (in $1000)	0.006***	0.003	0.008***	0.003***	0.023***	-0.050***
	(0.0002)	(0.0002)	(0.0001)	(0.0000)	(0.0001)	(0.0003)
Observations	1,589,110	1,682,872	1,688,784	5,614,647	5,616,582	2,046,161
Mean of outcome	-0.011	0.006	0.021	0.074	0.215	2.794
	Panel B: School-Grade Grade-Year Fes					
HVAC Upgraded	0.040***	0.025***	0.034***	-0.002***	-0.006	0.082***
	(0.010)	(0.007)	(0.007)	(0.001)	(0.005)	(0.021)
Observations	1,883,124	1,981,069	1,986,713	5,991,386	5,993,693	2,347,602
Mean of outcome	0.004	0.001	0.020	0.074	0.216	2.804
	Panel C: Controlling for 2019-2021 Test Score Change					
HVAC Upgraded	0.024***	0.034***	0.036***	-0.004***	-0.012***	0.117***
	(0.008)	(0.007)	(0.006)	(0.000)	(0.002)	(0.006)
Observations	787,471	873,963	877576	1577707	1577895	838473
Mean of outcome	0.013	0.010	-0.011	0.072	0.215	2.857

Notes: This table shows the results of models predicting student outcomes based on whether or not their school had received an HVAC upgrade. Panels A to C represent different modeling approaches. Panel A shows models with student, school, year, and grade fixed effects; Panel B shows models with school-grade and grade-year fixed effects; and Panel C shows results that include with school-grade and grade-year fixed effects, and control for the change in test scores from 2019 to 2021. All models also include student and district level covariates. Columns 1-6 present the results for different outcome variables. Standard errors are adjusted for clustering at the student level and are in parentheses. Coefficients labeled as ***, **, and * are statistically significant at the 1, 5, and 10 percent levels, respectively.

Table 3: The Effects of Air Purification Upgrades by Age

	(1) Test Scores	(2) Pct Days Absent	(3) Chronically Absent	(4) Grades
	Panel A: Grades 3-5			
HVAC Upgraded	0.032***	-0.006***	-0.018***	---
	(0.003)	(0.000)	(0.001)	
Observations	717,602	2,391,217	2391923	
Mean of outcome	0.005	0.065	0.187	
	Panel B: Grades 6-10			
HVAC Upgraded	0.042***	0.002***	-0.000	0.090***
	(0.003)	(0.000)	(0.001)	(0.003)
Observations	750,408	2,977,285	2978483	2046158
Mean of outcome	0.043	13.668	0.242	2.794

Notes: Columns 1-4 present the results for different outcome variables. These results come from models including student, school, year, and grade fixed effects and are run separately for students in grades 3-5 and grades 6-10. We use our primary specification, which controls for student and district covariates and student, school, year, and grade fixed effects. Standard errors are adjusted for clustering at the student level and are in parentheses. Coefficients labeled as ***, **, and * are statistically significant at the 1, 5, and 10 percent levels, respectively.

Table 4: The Effects of Air Purification Upgrades by Gender, Race and Income

	(1) Test Scores	(2) Pct Days Absent	(3) Chronically Absent	(4) Grades
	Panel A: Boys			
HVAC Upgraded	0.037***	-0.003***	-0.011***	0.089***
	(0.003)	(0.000)	(0.001)	(0.004)
Observations	862,349	2,873,737	2,874,784	1,043,831
Mean of outcome	0.002	0.076	0.221	2.654
	Panel B: Girls			
HVAC Upgraded	0.032***	-0.002***	-0.007***	0.090***
	(0.003)	(0.000)	(0.001)	(0.004)
Observations	834,949	2,737,485	2,738,376	1,001,075
Mean of outcome	0.040	0.071	0.208	2.940
	Panel C: Never Economically Disadvantaged Children			
HVAC Upgraded	0.042***	-0.002***	-0.009***	0.090**
	(0.004)	(0.000)	(0.001)	(0.003)
Observations	691,996	2,444,039	2,444,828	979,980
Mean of outcome	0.489	0.049	0.113	3.176
	Panel D: Always Economically Disadvantaged Children			
HVAC Upgraded	0.027***	0.003***	0.010***	0.036***
	(0.004)	(0.000)	(0.002)	(0.007)
Observations	512,491	1,655,319	1,655,984	536,736
Mean of outcome	-0.424	0.106	0.345	2.303
	Panel E: Non-Hispanic White Children			
HVAC Upgraded	0.033***	-0.003***	-0.011***	0.109***
	(0.004)	(0.000)	(0.001)	(0.004)
Observations	739,550	2,521,256	2,521,877	952,930
Mean of outcome	0.341	0.061	0.166	3.080
	Panel F: Black Children			
HVAC Upgraded	0.033***	-0.001***	-0.002	0.061***
	(0.005)	(0.000)	(0.002)	(0.006)
Observations	421,543	1,409,119	1,409,812	510,749
Mean of outcome	-0.417	0.091	0.279	2.415
	Panel G Hispanic Children			
HVAC Upgraded	0.023***	0.007***	0.017***	0.009
	(0.005)	(0.000)	(0.002)	(0.007)
Observations	344,686	1,101,245	1,101,674	388,635
Mean of outcome	-0.252	0.083	0.250	2.521

Notes: Columns 1-4 present the results for different outcome variables. These results come from models including student and district level covariates and student, school, year, and grade fixed effects and are run separately for the subgroup represented in each panel. Standard errors are adjusted for clustering at the student level and are in parentheses. Coefficients labeled as ***, **, and * are statistically significant at the 1, 5, and 10 percent levels, respectively.

Table 5: Effect of HVAC on Outcomes by Air Pollution Exposure

	Lower than Median Air Pollution				Higher than Median Air Pollution			
	(1) Test score	(2) Pct Days Absent	(3) Chronically Absent	(4) Grades	(5) Test score	(6) Pct Days Absent	(7) Chronically Absent	(8) Grades
HVAC Upgraded	0.027***	0.007***	0.032***	-0.061***	0.040***	-0.007***	-0.030***	0.212***
	(0.003)	(0.000)	(0.001)	(0.004)	(0.004)	(0.000)	(0.001)	(0.005)
Observations	834,471	2,778,526	2,779,569	1,031,668	758,820	2,551,724	2,552,471	912,783
Mean of Outcome	0.005	0.074	0.215	2.796	0.041	0.073	0.213	2.795

Notes: These results come from models including student and district level covariates and student, school, year, and grade fixed effects. Standard errors are adjusted for clustering at the student level. Columns 1-4 present the results for different outcome variables for schools with lower than median air pollution. Columns 5-8 present the results for different outcome variables for schools with higher than median air pollution. Standard errors are adjusted for clustering at the student level and are in parentheses. Coefficients labeled as ***, **, and * are statistically significant at the 1, 5, and 10 percent levels, respectively.

Table 6: Association Between HVAC Upgrades and Teacher Sorting

	(1) Teacher will return to school	(2) Teacher will return to NC	(3) Teacher years of experience	(4) Teacher has Graduate degree	(5) Teacher age	(6) Teacher is a minority	(7) Student Changed school
HVAC Upgraded	-0.016***	-0.005***	0.091	-0.001	0.189***	-0.000	0.007***
	(0.004)	(0.003)	(0.057)	(0.002)	(0.068)	(0.002)	(0.001)
Observations	342,897	342,897	362,319	362,319	360,939	344,884	5,616,582
Mean of Outcome	0.781	0.875	12.910	0.349	41.269	0.219	0.187

Notes: Columns 1-6 present the results for different teacher level measures. These results come from models which are run at the teacher-level and which include school and year fixed effects. In addition, columns 1 and 2 include a range of teacher level covariates. Column 4 is a student level model predicting student mobility and using student, school, grade, and year fixed effects. Standard errors are adjusted for clustering at the teacher level and are in parentheses. Coefficients labeled as ***, **, and * are statistically significant at the 1, 5, and 10 percent levels, respectively.

Table 7: Balance Test of School Level and District Level Factors Associated with an HVAC Upgrade

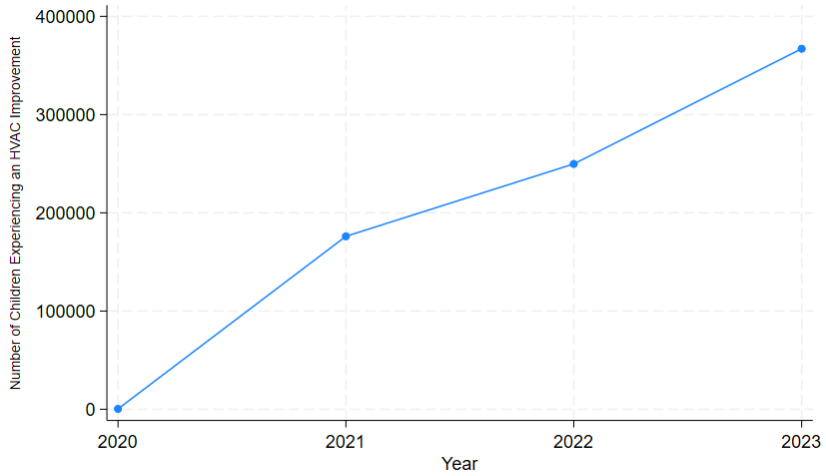
	Panel A: School-level Factors				
	(1) Economically Disadvantaged	(2) Log non-HVAC Expenditures	(3) District Percent Low Income	(4) % Black (by District)	(5) % Hispanic (by District)
HVAC Upgraded	-0.010***	-0.397***	0.144***	-0.003***	-0.003***
	(0.001)	(0.002)	(0.011)	(0.000)	(0.000)
Observations	5616582	5616582	5616582	5616582	5616582
Mean of Outcome	0.426	16.501	50.917	0.251	0.198
	Panel B: District Level Factors				
	(6) HVAC Upgraded				
Pandemic test score loss	-0.000				
	(0.000)				
Observations	1,578,274				
Mean of Outcome	0.127				

Notes: Columns 1-6 present the results for different outcome variables. The results in Panel A come from models including student and district level covariates and student, school, year, and grade fixed effects. The results in Panel B only include district, grade and year fixed effects. Standard errors are adjusted for clustering at the student level and are in parentheses. Standard errors are in parentheses. * $p < .1$, ** $p < .05$, *** $p < .01$

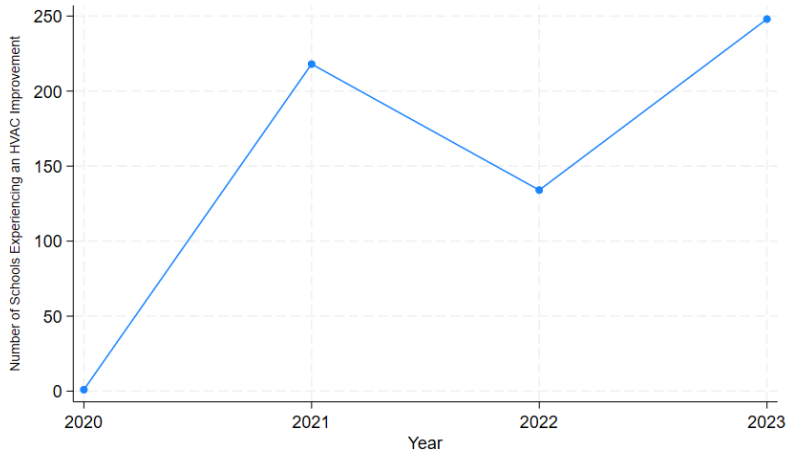
Figures.

Figure 1: Number of Schools and Students with HVAC Upgrades over Time

Panel A: Number of Children Experiencing an HVAC Improvement

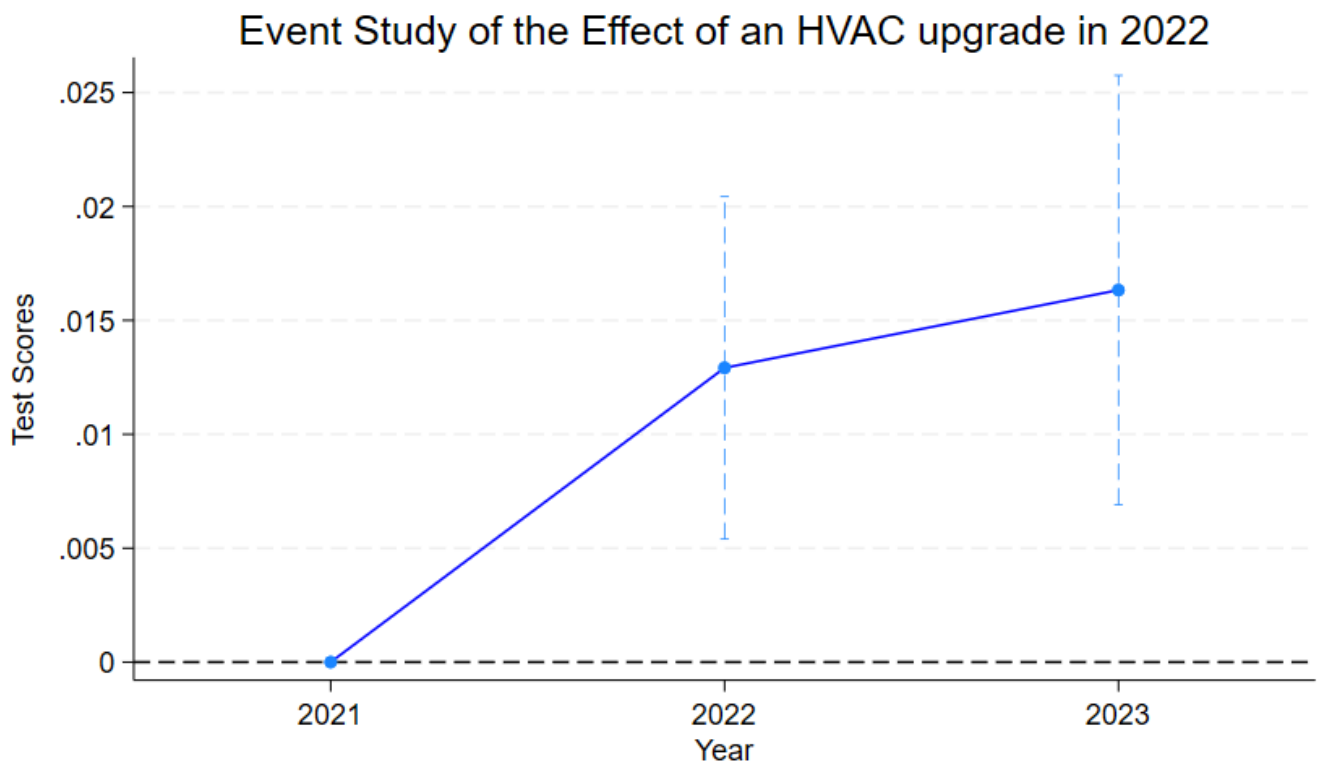


Panel B: Number of Schools Experiencing an HVAC Improvement Each Year



Notes: Panel A of Figure 1 shows the cumulative number of children experiencing an HVAC improvement over time. Panel B of Figure 1 shows the number of schools who upgrade their HVACs each year, which is part of our identifying variation.

Figure 2: Event Study of the Effect of HVAC Upgrades on Test Scores



Notes: This figure depicts and event study of the effect of getting an upgraded HVAC in 2022 on test scores, compared to students who did not experience an HVAC upgrade. We control for student and district level covariates and student, school, year, and grade fixed effects. Standard errors are clustered at the student level and appear at vertical dotted lines.